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[Continued on page (III) of Cover.

THE TROLLEYBUS

By G. F. SINCLAIR, Member.*

(Paper first received 6th June, and in revised form 1st August, 1939, and read before the NORTHERN IRELAND SUB-CENTRE 21st November, 1939. The paper would also have been read and discussed before THE INSTITUTION on the 9th November, 1939, but the meeting was cancelled owing to the war.)

SUMMARY

The paper relates to the trolleybus and the principles upon which this double-deck vehicle is now constructed. It is sectionalized under headings dealing with the design of the electrical equipment, the chassis transmission gear and running units, the construction of the trolleybus as a whole, the method of current collection, and the overhead transmission system. The final section of the paper reviews the various factors which have led to the adoption of the trolleybus in this country.

Throughout the paper the schematic diagrams which show the connections for the various apparatus described, and the drawings of the vehicular components, relate to the latest types of trolleybuses.

INTRODUCTION

The trolleybus has been adjudged by the Ministry of Transport an electric vehicle, and its construction and operation are governed by the Ministry's regulations. Its principles are founded on street electric traction practice. The supply to the overhead system being 600 volts, direct current, the development of the electrical equipment has proceeded along conventional lines.

In this country, single-motor drive to the back axle is universal. The rating of the motor selected for the work depends upon the duty or load cycle of the services. The various routes which may comprise a service are influenced by such known variables as maximum speeds, stops per mile, and lie-over times, all of which can be shown on speed/time curves. The traffic congestion on services cannot be calculated; it is due to delays arising from traffic signals, slow-moving traffic, and reduced speeds because of road conditions. These unknown quantities can be recorded graphically by an instrument which can be operated on a vehicle over the routes and will produce a service speed/time curve taking care of all variables. With this information the rating of the motor can be established, but as a check to determine the capacity of the motor in relation to the services, tests are usually carried out to measure the root mean square currents and motor temperatures when operating under service conditions. For these tests the thermal-storage r.m.s. meters measure the main and shunt fields r.m.s. currents. Thermometer measurements are recorded of the field and armature temperatures.

Tests have been taken with a trolleybus, equipped with a single compound motor arranged for rheostatic braking, and loaded to 11 tons 12 cwt., on a level route which could be termed heavy-duty and congested. The schedule speed of the route was 10.79 m.p.h., and the average speed, i.e. excluding standing time at termini, was 11.45 m.p.h. The loadings can be con-

sidered to be above the average at 25 passengers per car mile, and the proportion of time at rest in relation to running time (excluding time at termini) was 12 per cent. The r.m.s. armature-current value was 103 amperes, the shunt-field current 3 amperes, and the highest temperature-rise (by thermometer) was 70 deg. C. in the main field and interpole. The characteristics of services have been found to have sufficient similarity to allow for standardization on 3-axle trolleybuses weighing laden $13\frac{1}{2}$ tons with a 95-h.p. motor rated at 550 volts and with a lower-rated machine for use of two-axle vehicles.

The driving of the trolleybus resembles that of an automobile, but with two pedals instead of three. Electromagnetic contactors are controlled by a pedal-operated master controller. The control gear has been developed for use with a single driving motor, which avoids the complication of series-parallel control. Comparing a single-motor drive with the use of two motors, the loss of energy in the starting resistances in the case of the single motor is more than offset by the mechanical and electrical advantages in regard to maintenance and lower capital cost. The yearly cost of energy for a trolleybus taking energy at 0.5d. per unit amounts to some £286, assuming an annual mileage of 50 000. The saving which would result from the use of series-parallel control would be in the neighbourhood of 8 per cent, the precise figure depending upon the service.

The explanation given later in the paper of the details of the development for the suppression of radio interference generated by trolleybuses, shows that considerable attention has been paid to this field, to ensure uniform suppression over all broadcast bands.

The overhead system is constructed for feeding in sections not more than $\frac{1}{2}$ mile in length, and in many cases the supply is not earthed. This unearthed method of distribution has the advantage of minimizing the effect of the accidental earthing of a conductor, and of limiting the maximum leakage current on the vehicles.

ELECTRICAL EQUIPMENT

Motor

The type of motor which is most suitable for trolleybus work has a wide range of speed variation and limited maximum values of braking torque. In the earlier equipments use was not made of electrical or dynamic braking, but this practice was found to result in excessive brake-lining and brake-drum wear with heavy vehicles on services with frequent stops. The necessity for retarding the vehicle by reversing the torque of the motor forced the trend of development towards a machine the characteristics of which enabled the desirable features of acceleration and retardation to be embodied in the design of the motor.

* London Passenger Transport Board.

With single-motor equipments, field regulation is practised. The speed on the level with full field and with the line resistance cut out is approximately 12 m.p.h. Such performance can be met by either the regulated-field series motor or by a compound motor, both machines running as series motors at the maximum speed. The method of field-weakening adopted in order to reach the maximum speed is that of field shunting or tapping in the case of the series motor, and that of inserting resistance in the shunt field and diverting the series field in a compound machine.

With the regulated-field series-wound motor acting as

wheel-skidding and limits the stresses which can be applied to the transmission system.

The characteristic of the compound motor permits of regeneration to the line being obtained on the accelerator pedal, which can effectively reduce the speed of the vehicle to 15 m.p.h. A transmission brake on a trolleybus which has a retarding torque of a value less than the maximum accelerating torque and is operated by the backward movement of the power pedal is a valuable asset in driving. When the supply line is receptive, this regenerated current results in a reduction in energy consumption.

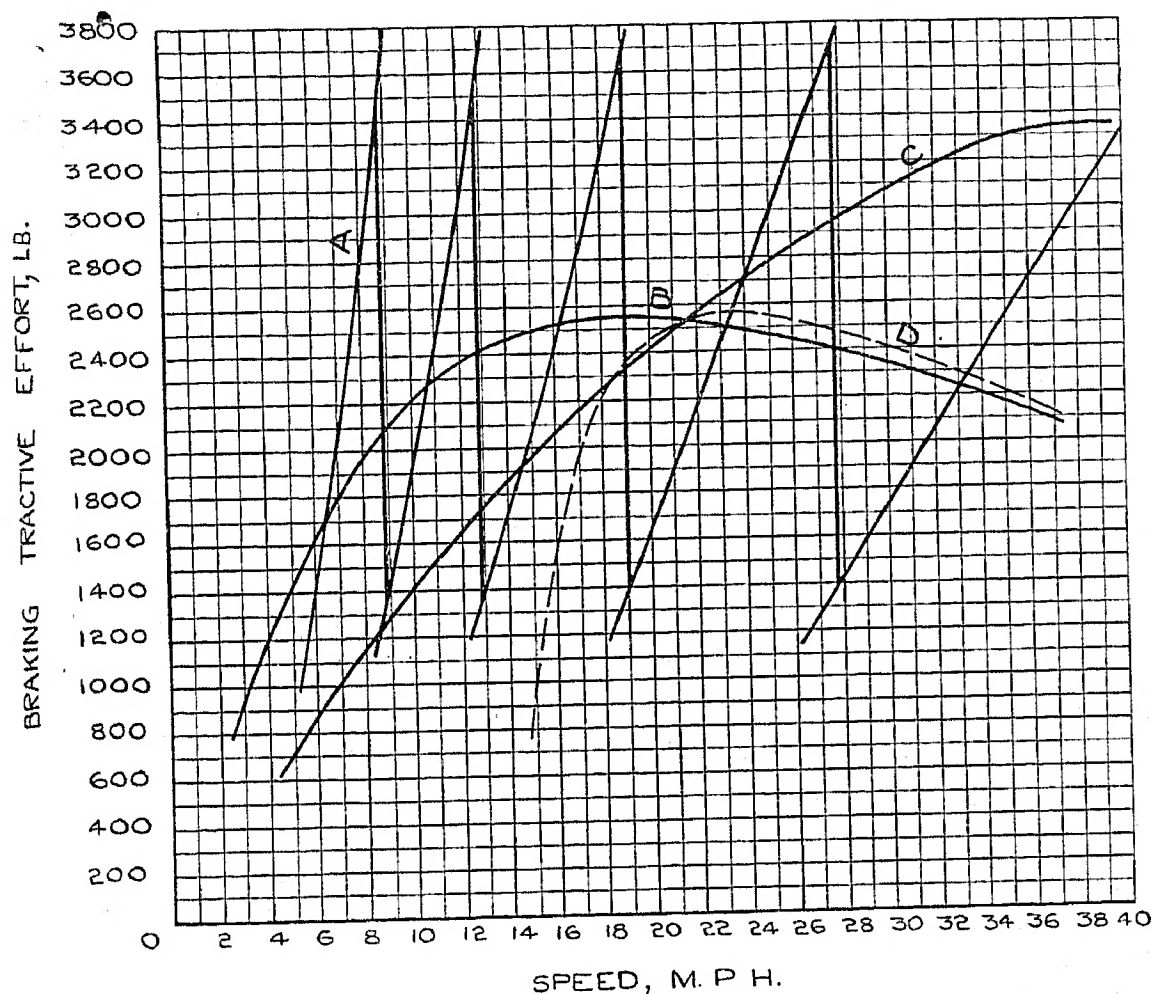


Fig. 1.—Rheostatic braking curves for similarly-rated series, compound, and shunt-wound trolleybus motors.

A. Series motor.
B. Compound motor.
C. Shunt-wound motor (shunt winding used primarily for braking).

a series generator on rheostatic braking, excessive braking torques are difficult to control at high speed, although by the use of current-limiting relays the maximum braking currents can be limited. Rheostatic braking curves are shown in Fig. 1; for the series generator five braking curves are given, arranged so that the average value of the braking is approximately the same as that obtained with the compound motor. The other curves have been taken on similar-capacity motors, and the irregular nature of the braking with the series motor as compared with the even braking of the compound motor is apparent.

On rheostatic braking, with a compound-wound motor, compound excitation controls the braking currents. During braking, the series field opposes the shunt field, and it is this action of the series field which gives automatic regulation of the braking effort down to a trolleybus speed of 4 m.p.h. Such a characteristic prevents

There are varying degrees of compound excitation on trolleybus motors, and the ratio of series-field winding to shunt winding is a matter of individual design. The use of a strong series field and a relatively light shunt winding with tapings on the series windings for speed regulation has been adopted. The shunt field augments the series during motoring, and thus is capable of providing a small amount of regenerated current, in the neighbourhood of 40 amperes. On rheostatic braking the shunt field only is used. The amount of regeneration is sufficient to give a braking rate of approximately 1 m.p.h. per sec. from 30 to 20 m.p.h. High regenerative voltages are overcome, which reduces the substation problems when there is not sufficient load on a rectifier section to absorb regenerated current. Curve C in Fig. 1 shows the braking effort obtained by using a shunt field primarily for braking requirements. The rheostatic

braking in this design does not include any series-field decompounding, the braking current being determined by the shunt field strength and braking-resistance value. The curve shows the high braking effort at speed, varying with the speed of the vehicle, due to the absence of the

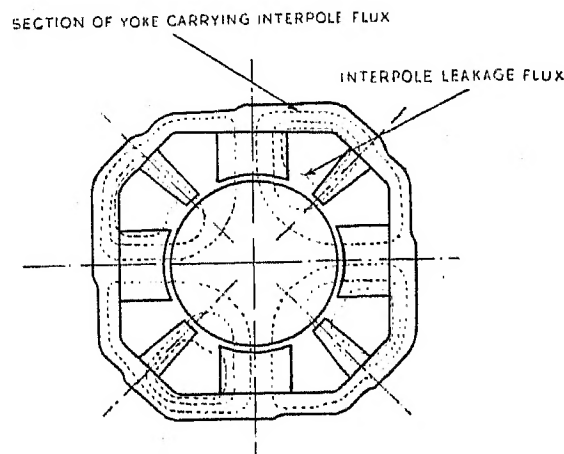


Fig. 2.—Section of the cast-steel motor frame.

opposition of the series field. It will be seen that modifications to the ratio of series windings to shunt windings can produce characteristics which would be suitable for any particular service.

The factors controlling the design of the trolleybus motor are weight, restricted dimensions, commutation

mutator is necessary than would be the case if a 2- or 3-turn armature were used, but the advantage of a single-turn winding lies in the good commutation. Notwithstanding the larger number of commutator bars used, no mechanical weaknesses have shown themselves in the bars, which are of a reduced cross-section.

A feature in the design of motor frame necessary to obtain good commutation over a wide range of current and flux variation is shown in Fig. 2. It will be seen that the yoke sections are thickened-up in the parts required to carry the interpole flux in addition to the main flux, the aim being to give as nearly as possible uniform flux density at all cross-sections under conditions of heavy load. It is of interest to note the arrangement of field windings, as shown in Fig. 3. The main coils consist of series and shunt sections which are wound on separate formers and separately insulated before being assembled. The shunt winding is of asbestos-covered wire, and the series and interpole coils are wound in the usual manner with asbestos-paper separators. Unlike the earlier experiences with shunt windings on traction motors, the modern method of winding has given and is giving reliability in service.

The trolleybus motor is usually placed under the floor of the vehicle, and arrangements must be made to ensure that the level of the sounds emitted from the motor is less than the level of conversation inside the vehicle. The low-pitched noise from the impacts of the chassis running

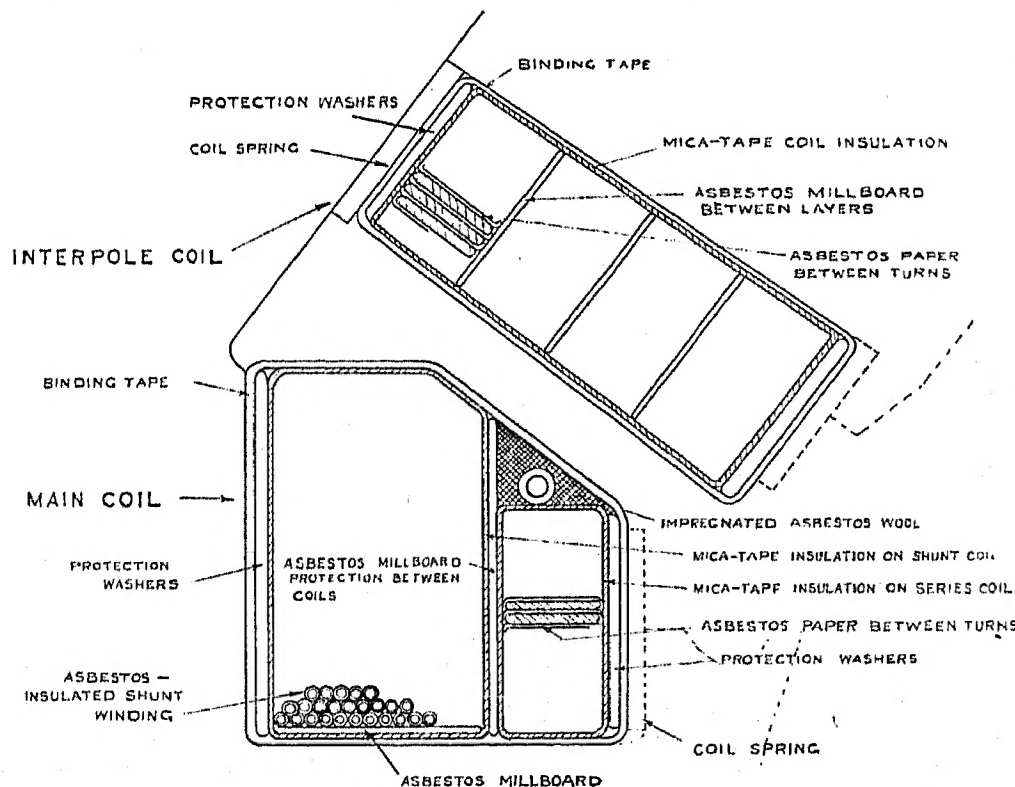


Fig. 3.—Arrangement of field windings for a compound motor.

under peak loads as a motor and, alternatively, as a generator, and the absence of sound. The first two essentially control the other factors, as it is an adjustment in design to give the best results which is ultimately produced. The most difficult problem is to secure a quality of commutation which will not cause deterioration of the commutator surface over a long period of operation, taking into account the extreme range of variations in the current, flux, and speed of the machine.

With this object, a single-turn winding is employed so as to reduce the reactance voltage. A larger com-

units and the continuous sounds from the driving gear may be termed "moderate" noises. As regards the motor, the loudness of the tone of the brush chatter on the commutator is greatest at low speeds and the noise from the motor fan greatest at high speeds. Brush commutator noise has not been eliminated, but considerably reduced. Fan sounds have been reduced in intensity by the use of an aerofoil form of fan and the adoption of a suitable arrangement of the air outlets. Magnetic hum has been obviated by trial and error as to the best proportion of the main-pole gaps. A test made by means of

an objective noise-meter on trolleybuses in service gave measurements of only moderate noise, with no high tones or loud notes.

Control Gear

In the schematic diagram shown in Fig. 4 a typical control circuit for a single-motor equipment is given. The number of contactors is 10, including 7 for operating in the armature circuit and 3 in the shunt field. The relays giving protection against overloads and over-voltage are

netic lines of force are used, there being no leakage as the air-gap between the plunger and the core is in the centre of the coil. Owing to the limited dimensions allowed in the construction of contactors, the coils and the plunger diameters are reduced to a minimum. This limitation in size necessitates high density of flux in the air-gap between the plunger and core, obtained by a comparatively large number of turns on the operating coil. The breaking of the circuit causes a high induction in the coil, the effect of which on the other equipment can be

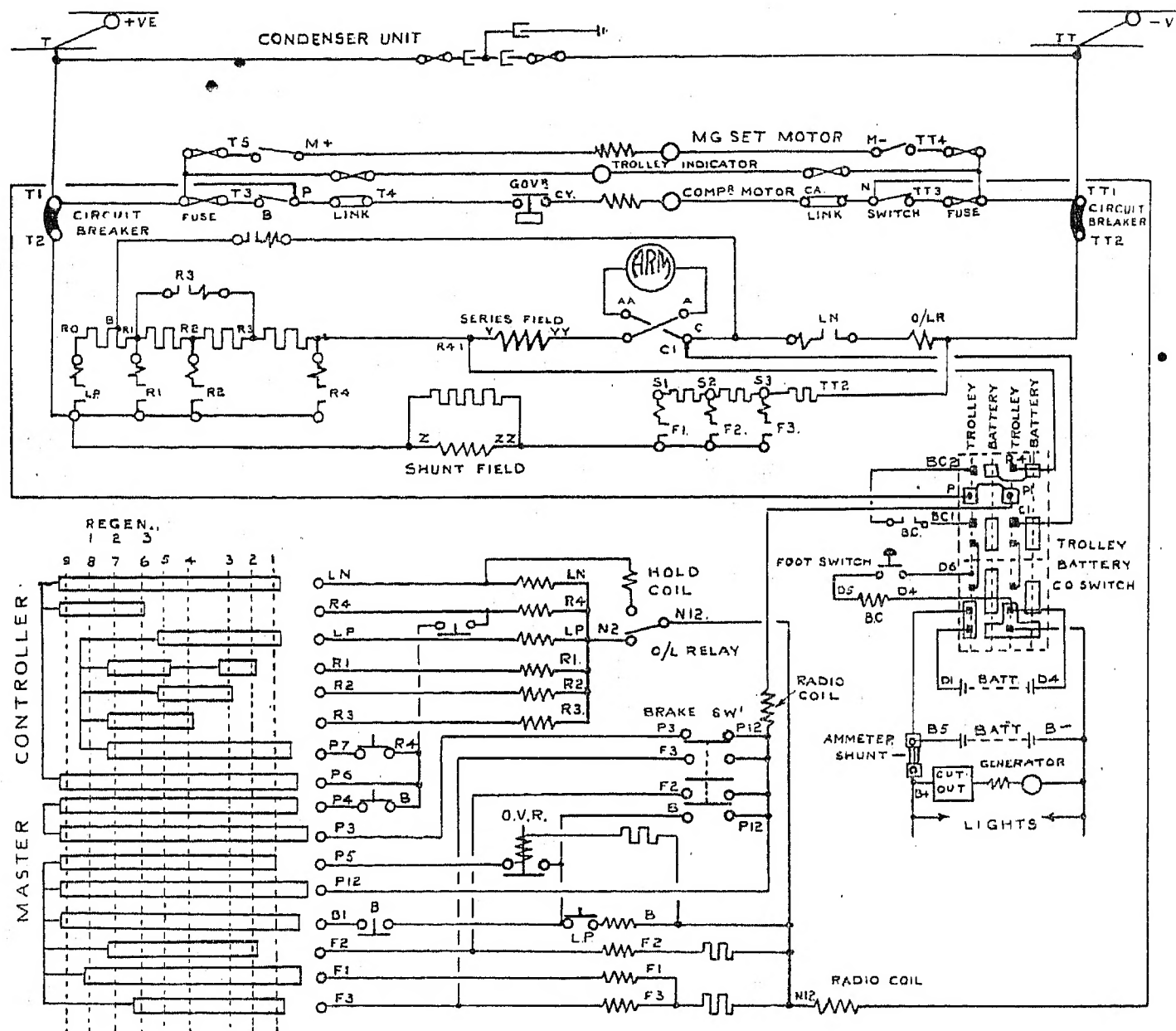


Fig. 4.—Schematic diagram for single-motor equipment.

interlocked with the main contactors. In trolleybus operation the majority of failures which cause delays of 5 minutes or more in service are attributable to control defects. A description will now be given of the type of contactors which experience has found to be the most reliable in service, together with other salient control features.

Contactors

In remote control of the electromagnetic type the contactor is in some respects the most important apparatus used. The power unit on the contactor is a line-energized coil which operates a plunger or a clapper forming the armature. With the plunger-type contactor all the mag-

netic lines of force are used, there being no leakage as the air-gap between the plunger and the core is in the centre of the coil.

The contactor with the clapper type of operation has to be designed with a comparatively large-size core, to take care of magnetic leakage. There being no air-gap in the core, the magnetic flux can be used at a high density, with a small number of ampere-turns to maintain this. The clapper is made with a surface area greater than the end of the core, which gives a low density in the air-gap between the two, and allows a coil to be used with few ampere-turns and therefore less induction. Mechanically, the clapper type of contactor, compared with the plunger type, is of simpler construction, having more robust wearing parts. The armature pin takes the place of the

solenoid spindle and bushes, which are subject to wear. In Fig. 5 a typical clapper-type contactor is shown, with the magnetic lines of force. A large clearance is obtained between the clapper and the core, which allows for

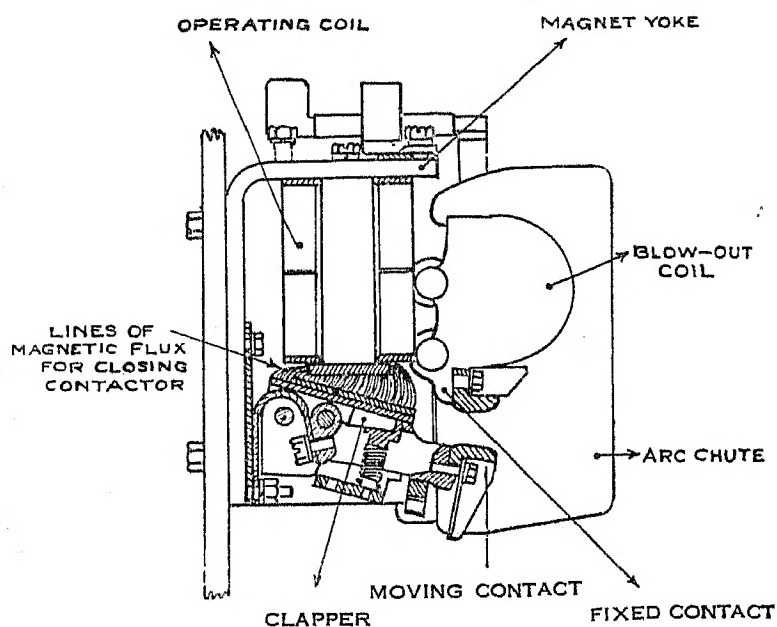


Fig. 5.—Clapper-type contactor, showing the path of the magnetic lines of force.

mechanical wear without disturbing the electrical performance.

Brake Switch

The schematic diagram shows the rheostatic-brake switch as a separate unit, and on the vehicle it is directly operated by levers from the brake pedal. An alternative arrangement is to incorporate the brake switch in the master controller, which is usually mounted under the driver's seat, allowing for a straight-line operation with the brake pedal. The brake pedal is insulated from the switch or master controller and the operating rod is in tension.

Protective Relays

The over-voltage relay seldom comes into operation—only on occasions when the regenerated voltage exceeds the line voltage and no other vehicle is on the particular section. The setting is at 680 volts when a line voltage of 600 volts is used. The operation of the over-voltage relay automatically open-circuits the power contactors and inserts resistance in a closed motor circuit. To reset after the operation of the over-voltage relay, the master controller has to be returned to the "off" position.

In addition to the normal protection afforded by two automatic circuit-breakers, an overload relay is used. The relay is operated at a current value below that of the circuit-breaker setting, and once tripped is held open by a high-resistance coil energized in all running positions of the master controller, so that it is impossible to reset the relay except in the "off" position of the controller. The circuit-breakers do not operate on normal overloads, but relieve the contactors from the necessity of breaking excessive currents. The action of the overload relay opens the main contactors, which break the circuit. It is usually found that uniform breaking between two or more contactors is not always obtained, one contactor doing most of the work.

Operating Coils

The use of enamel-insulated wire for the winding of the operating coils of contactors has become universal. The results have justified this type of insulation as compared with cotton-covered wire, which, when used, increases the external diameter of the coil and restricts the radiation of heat between turns. With enamel-covered wire, provision has to be made for the expansion and contraction of the wire. The inductive nature of the circuits creates high induced voltages, sometimes about twice line voltage, which the insulation must withstand.

Battery Operation

The battery change-over switch has proved itself to be a valuable addition to the control equipment. The switch is operated by the master-controller reverser key, which ensures the master controller being in the "off" position before the switch is moved. The function of the switch is to place the batteries in series for propelling the vehicle. The no-load voltage with the batteries in series is in the proximity of 70 volts and gives a trolleybus speed of 5 m.p.h., the shunt field of the compound motor not being energized. For emergency purposes, the arrangement described has been most beneficial in traffic.

Brakes

The rheostatic and air brakes are controlled by a single pedal. The first movement of the pedal open-circuits the control and applies the rheostatic brake; in the final section of travel, rheostatic and air braking are combined. The reciprocating type of air compressor is favoured, driven by a totally enclosed line-operated motor. Mechanically driven compressors present problems owing to the wide speed-range of the trolleybus driving motor or propeller shafts, resulting in excessive compression at high speeds which is difficult to off-load economically. For driving the compressor, and to provide against the possibility of leakage in the air system, a $\frac{3}{4}$ -h.p. continuously rated series motor is used which is usually constructed with two main poles. The design of motor fields maintains a relatively low voltage between the commutator bars—a good feature with small-diameter commutators. The air-brake reservoir stores braking power sufficient for 15 normal brake-applications. The precautions which are taken in the control equipment to prevent the operation of the trolleybus without braking power will now be described.

The compressor-motor circuit is controlled by the main control switch, which makes it impossible to energize the control gear without starting up the compressor motor. This ensures against the possibility of operating the vehicle without switching on the air brake and provides against faults in either circuit, as the two are fed through a common fuse. To give an immediate indication to the driver of the loss of air pressure in the reservoir, an audible and visible alarm is fitted which comes into action when the air pressure falls below 45 lb. per sq. in. This alarm is energized from the low-voltage supply and, in addition to warning the driver of low air-pressure when the trolleybus is in service, provides an indication as to whether the air-brake equipment is satisfactory before the vehicle is taken into service.

Low-Voltage Lighting*

There are three methods of driving the low-voltage generator—direct drive from the main motor shaft, belt drive from the propeller shaft or coupling, and the use of a high-voltage motor. All these are mechanically and electrically satisfactory; the selection of the method to be employed must be determined by service requirements.

The percentage of time during which the lighting load has to be maintained by the battery, with mechanically driven generators, depends on the characteristics of the service. On a trolleybus route in London, between Shepherd's Bush and Uxbridge, some interesting results were obtained showing the extent to which the charging of the batteries is dependent on the running time in service. The total time to cover the route was 131 min. 40 sec., and the time for which the trolleybus was stationary was 36 min. 50 sec. Thus the total vehicle moving time was 94 min. 50 sec., i.e. only 72 per cent of the total route time. The route could be described as an open town route; the schedule speed was 11.64 m.p.h., including lie-over time at termini, and this represents a higher percentage of running time than would be experienced in a more central area. The 1 600-watt (1-hour

advantage with the motor-generator set of being able to charge the battery at will is of value when the battery is used to any extent for traction purposes.

As the Ministry of Transport regulations require double insulation between the low-voltage wiring and parts connected with the 600-volt supply, in the early motor-generator sets the motor was mounted on a bedplate through insulating rubber bushings, the drive to the generator being through a rubber coupling. It was found that this construction was liable to give rise to vibration, and the bedplate was an unnecessary additional weight. A motor-generator designed as a single-shaft machine has since been developed. The motor armature is electrically insulated from the generator armature by a moulded micanite cone, in a similar manner to the insulation of a commutator from its bush. The high- and low-voltage yokes are insulated from one another, and, in order to prevent the common shaft from short-circuiting the two, the bearing housing at the motor end is insulated by means of micanite.

A shunt winding on the motor is not used, because of the thin wire necessary in the shunt-field coils. A series-wound motor is more capable of withstanding voltage

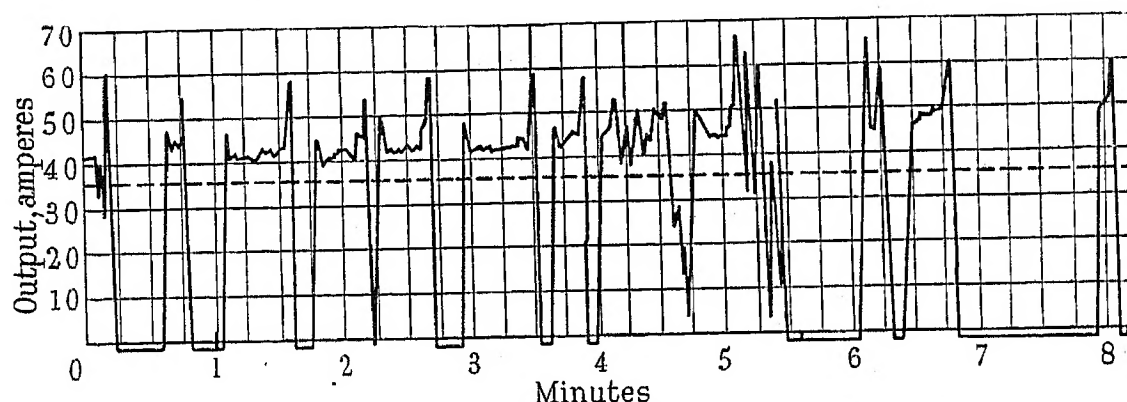


Fig. 7.—Curves showing comparison between belt-driven generator and motor-generator.
Belt-driven generator ————— Motor-generator - - - - -

rating) dynamo used in the test was belt-driven from pulleys on the motor coupling having a ratio of 1.2 to 1. The ampere-hours required for the lighting load over the journey were 59, and the generator gave during the run 81 ampere-hours, measured with meters on the vehicle. On this route 30 per cent of the vehicles operate for 7 hours per day, and the remainder for 17 hours. The performance of the generator was equivalent to maintaining satisfactory battery condition on a winter service where the lighting load is necessary throughout the whole running time, which would occur with all vehicles operating in the early morning and evening only. (See Fig. 7, which shows graphically the results of the test over a small section of the route.)

During fog running or a dislocation of traffic, the margin of generated amperes would not be sufficient to avoid the batteries becoming discharged when battery manoeuvring occurred in service. The motor-generator set for lighting gives constant vehicle illumination irrespective of the trolleybus speed or battery condition, a feature which is of special importance in dense traffic. The battery, which is usually of 96-ampere-hour capacity, is mainly used for vehicle manoeuvring and for a certain amount of lighting whilst the trolleybus is in the depot for cleaning. The

* Compulsory on metal bodies.

surges, owing to the undamped condition of the field giving greater stability against flashovers than a shunt winding. [The results obtained in oscillograph tests are shown in Fig. 6 (see Plate, facing page 232).] It is, however, necessary to provide some means of preventing the speed from becoming excessive on no-load. The motor fan gives a load sufficient to restrict the speed to 5 000 r.p.m., but, in order to reduce the speed further, a permanent load is connected across the generator.

Production of Electric Charges on Trolleybuses

There are three conditions under which trolleybuses may become electrically charged in service, namely electrostatic charges produced by the friction of the tyres on the road surface; rise in potential due to the inductive kick from the contactor coils and motor circuits or from induction from transmission mains; and, lastly, the vehicle may become a conductor when a leakage occurs from the power circuits to the body. These conditions are very unlikely to occur, and in any event present little inconvenience to the travelling public.

The first condition—of the vehicle receiving an induced charge from either the tyre or the road surface—is common to all rubber-tyred vehicles with metal or composite bodies. The generation of a charge depends largely on

the road surface. With dry clean granite sets, voltages up to 900 volts can be measured by an electrostatic voltmeter immediately after the vehicle comes to rest. On an asphalt or tar-macadam road, zero readings are registered. The second condition—of inductive charges from the electrical equipment when circuits are broken—gives voltages up to 300. The electrostatic voltmeter used for these tests had an undamped movement, so that the readings can only be described as the mean volts. Neither of these types of charges necessitates special precautions, as the frequency of loading and unloading passengers prevents high static charges from being built up, and, in the case of induction, the passengers would have to come into contact with an uninsulated portion of the vehicle at the moment of breaking the inductive circuit. The use of low-resistance tyres of about 2 000 ohms (measured from the tread to the wheel rim) will satisfactorily earth these charges.

It is the possibility of electrical leakage from the

potential equal to that of the overhead supply across the whole insulation. The connections are shown diagrammatically in Fig. 8. The use of the insulated sections on the overhead lines allows for the automatic reversal of the polarity as the vehicle passes. This has been found necessary as it is possible to have satisfactory insulation readings, below the 3 milliamperes permitted by regulations, with the current flowing through the equipment in one direction, whereas, with the current reversed, the insulation values are unsatisfactory. For purposes of safety, the test plug or spade is permanently connected to earth and the milliammeter connected to the negative supply by pressing a push button on the test panel; thus the plug cannot be alive when handled by the tester.

The trolleybus is designed to ensure secondary and, where possible, tertiary insulation on all high-voltage components. The nightly test is between the conductors and the body or chassis, the secondary insulation being short-circuited. Every 14 days each high-voltage circuit is tested individually, including all insulation whether primary or secondary.

The insulation of the platform consists of a rubber mat secured to the floor boarding by an adhesive. The handrails have an insulated covering and are provided with secondary insulation, the combined arrangement giving insulation-resistance readings of infinity.

Suppression of Radio Interference

The British Standards Institution has recently published a Specification setting out three methods for reducing the electrical interference generated by trolleybuses.

A large-scale experiment has been carried out in London on trolleybuses with chokes at the contacts of the master controller, on each side of the contactor interlocks and auxiliary contacts. This method gave satisfactory suppression over the prescribed range of wavelengths. The coils were lightly rated and gave trouble under partial fault conditions before the control fuse was blown. There are 19 chokes required to suppress the control interference alone, and this additional equipment caused complications.

The system now adopted includes only two liberally current-rated chokes, one in each of the two main master-controller feeds, in conjunction with a centre-tapped condenser filter connected across the line and chassis. The two control chokes do not adequately suppress the control interference, as the chokes are placed some distance away from the source of interference and because the intervening control wiring induces in the power wiring interference which is carried direct to the overhead system. To reduce this by-pass effect, a centre-tapped condenser filter is used which tends to short-circuit the high-frequency potentials appearing between the trolleys and the chassis. The condenser filter or capacitor also provides efficient suppression of interference in the main motor, the motor-generator set, the compressor motor, and the power arcs on the contactors, within the wavelengths of 1 500 to 200 metres. The average signal/interference ratio of 25 db. obtained over these wavelengths compares favourably with the results obtained from the vehicles equipped with individual chokes.

The position of the apparatus can be seen in Fig. 4.

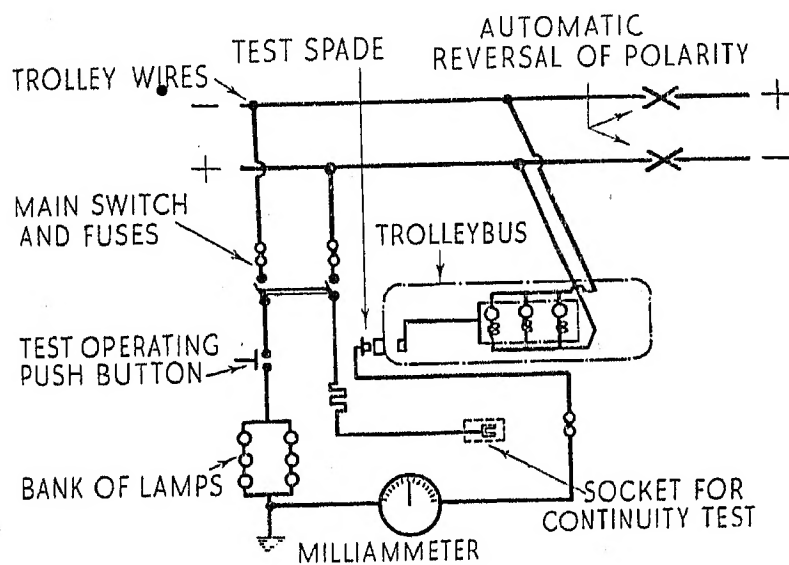


Fig. 8.—Diagram of connections used on the panels at the entrance of depots for nightly testing the insulation of trolleybuses.

600-volt circuits which has to be guarded against, the vehicle being in reality unearthed. The Ministry of Transport regulations call for a daily test of the insulation of each trolleybus. The test is accomplished after the vehicle has completed each day's service, testing apparatus being located at the entrance of the depots. This enables the test to be carried out with the trolleybus in the condition in which it has been operating, an especially important point in wet or snowy weather, as the insulation resistance varies with the climatic conditions. For convenience in testing, the frames of the individual 600-volt units are connected by means of cables to a common testing receptacle, which is mounted at the back of the trolleybus underneath the platform. The test panel fixed in the depot consists of a plug, designed to fit the test socket on the vehicle, attached to a lead which is in series with a high-resistance milliammeter connected to a limiting resistance formed by a bank of lamps, and thence, through fuses, to the negative overhead wire.

When the plug is inserted in the trolleybus testing receptacle and power is applied through the control gear in the usual manner, all units being energized, there is a

MECHANICAL PARTS

Chassis

The automobile design of chassis used in public-service vehicles has been adapted to trolleybus operation. The orthodox pressed-steel side members are used, and the springs, beside taking the loads, provide the reactions to traction and braking efforts. With the 3-axle trolleybus the two rear axles are driving axles. In the majority of cases a third differential is used. It is only proposed to describe the variations which trolleybus requirements have necessitated as compared with the lighter transmission loads and lower propeller-shaft speeds standardized in most types of heavy-automobile practice.

The design of worm gears employed in the rear-axle drives is generally in accordance with the British Standard Specification based on the involute helicoid worm. The selection of worm drives in preference to the bevel-wheel types was influenced by the ease of accommodating high ratios between the driving shafts and axles, the quietness of running, and the low height obtainable by the use of underslung worms.

The load capacity of the worm gear when driven by an electric motor has to be substantially greater than with the oil-engine drive, to provide for the high sustained torque on the worm wheel during acceleration. This has been found by observation in service to require over 20 per cent greater torque capacity. On single-axle drives, 8½-in. worm-gear centres are frequently used, and 7-in. or 8-in. centres where the drive is divided between two axles. This is much above the calculated load capacity required, but has been adopted as a result of experience with the heavy momentary overloading of the transmission during acceleration.

The design of the propeller shaft is the result of research over a number of years. In its present-day form it has played a big part in the improvement of the general arrangement of the trolleybus chassis and body. With its use a better disposition of the electrical equipment is obtained, and a greater freedom in body design.

In automobile practice the prime mover is generally mounted at the front of the vehicle, and lengthy propeller shafts transmit the power to the driving axle. With the high propeller-shaft speeds (up to 3 000 r.p.m.) experienced in trolleybus operation, it was necessary to design transmission shafts so as to reduce vibration to a minimum. This requirement was not met by mounting the electric motor at the front of the chassis, and providing long shafts with centre bearings and many couplings.

The Ministry of Transport's regulation whereby 10-in. clearance under the vehicle must be maintained 13 ft. from the front of the 3-axle trolleybus, encouraged the placing of the motor on the chassis beneath the floor close to the driving axles, in which case only a single short shaft is necessary.

Numerous experiments were undertaken to determine the design of a shaft which would be free from vibration up to the maximum trolleybus speed, and to ascertain the true critical speed of such a shaft. These investigations were successful, as is proved by the wide use of the short single-shaft drive.

With the short-shaft drive the line through the transmission from the motor shaft to the leading axle with an

unladen vehicle allowed for a working angle on each of the universal joints of 2°, which was partly obtained by the tilting of the worm shafts. Heavy emergency braking causes relative movement between the driving bogie and the motor, which increases the normal working angle of the shaft, so that the universal joint assumes a working angle of 4°. With these conditions and with a shaft approximately 28 in. in length, smooth running is obtained. The vibrograph tests taken on a trolleybus showed freedom from vibration up to a speed of 35 m.p.h. in normal operation, and under heavy braking conditions with the maximum angular variation of the couplings very little noise or vibration was apparent, even when passing through the true critical speed of the shaft at 1 400 r.p.m.

The Chassis-less Trolleybus

With the introduction of the all-metal body for passenger road vehicles came a new conception of vehicular design, in which the chassis frame was no longer regarded as a necessity for supporting the body. With a coach-built body the chassis is essential for mounting the power unit and for anchoring the springing systems. The all-metal body, on the other hand, can form part of a chassis-less vehicle having inherently the structural strength necessary for the various loads. In such a system of construction it is possible to make better use of the materials, heavy sections being used where justified and the vehicle being designed as a whole instead of in two parts.

The forces which subject the structure of a vehicle to the greatest stresses cannot be determined by static methods. The longitudinal forces of acceleration and retardation and the lateral stresses due to centrifugal forces on curves and wind pressure make up the working loads on the body structure. The reactions to these forces can be more adequately provided for in a unit-built vehicle. The overturning moment on a chassis-built trolleybus due to lateral forces is resisted through the chassis frame and the bulkheads. The longitudinal stresses are taken by the body pillars and racking plates, the latter ensuring a division of the loads between the various pillars. The strength of the design to resist lateral stresses depends upon the fixing of the body cross-members to the chassis frame. This connection is usually made through fibre blocks or rubber mountings on out-rigger brackets. The absence of a permanent and firm fixing detracts from the rigidity of the structure and tends to upset the balance of load on the members.

With the chassis-less vehicle there are no cross-bearers carrying the structure; the members form an integral part of the framing. The bulkheads take the form of deep girders, with heavy transverse pressed-steel stiffening channels at the bases, riveted to the longitudinal members. When a rigid fixing is provided for the individual side-pillars there is no necessity for the pillar positions to coincide with cross-members. A better distribution of loading between the side pillars removes some of the tension stresses in the racking plates. The method of support of the bulkheads to and between the side framing gives the necessary stiffness to the structure which fits it to resist lateral forces.

One of the latest examples of chassis-less trolleybus construction is shown in Fig. 9. In this design the body

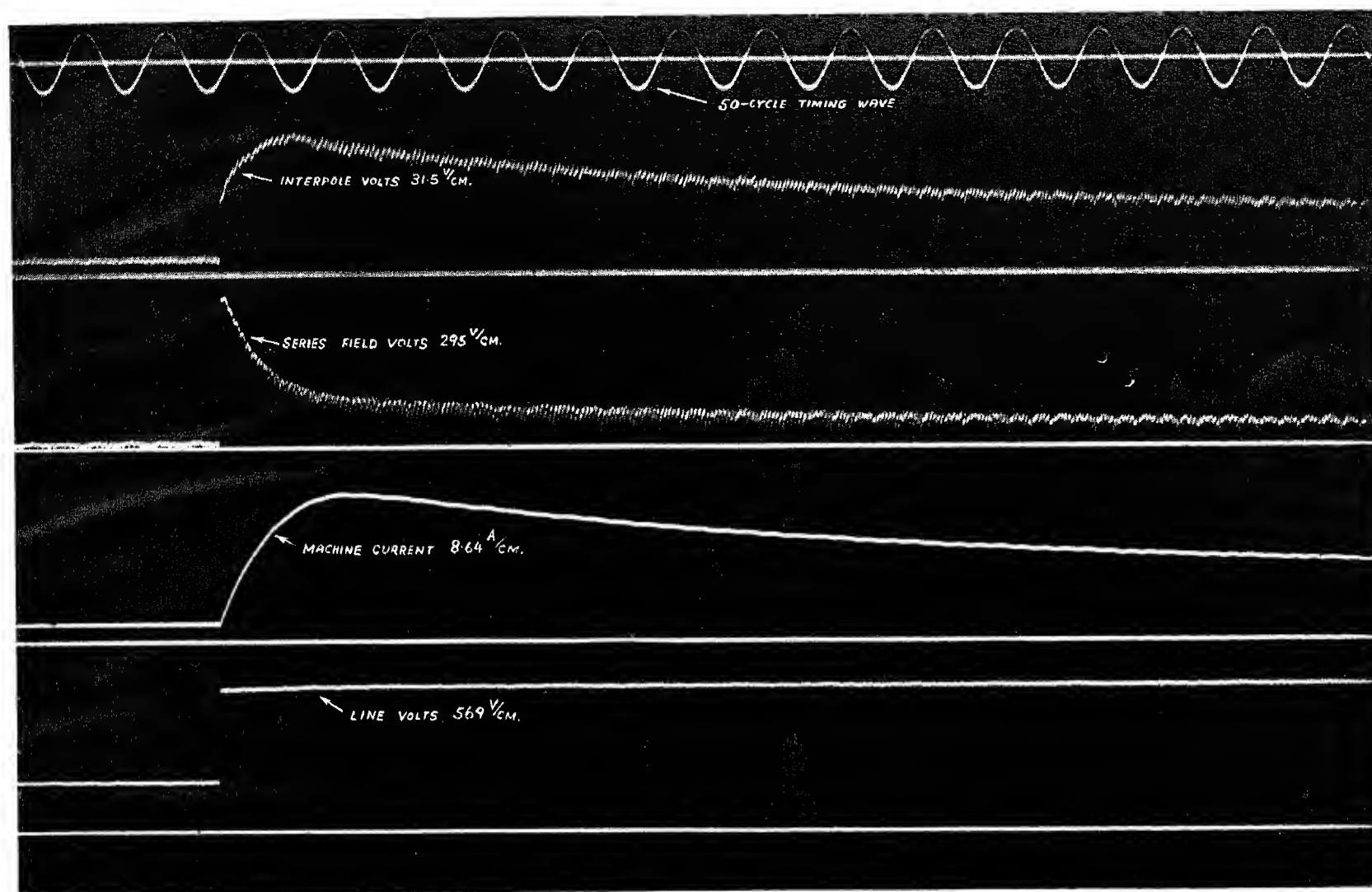


Fig. 6.—Oscillogram illustrating the conditions obtaining during a voltage surge from 500 to 1400 volts. Current rises to a value of several times the normal but the motor-generator does not flash-over.

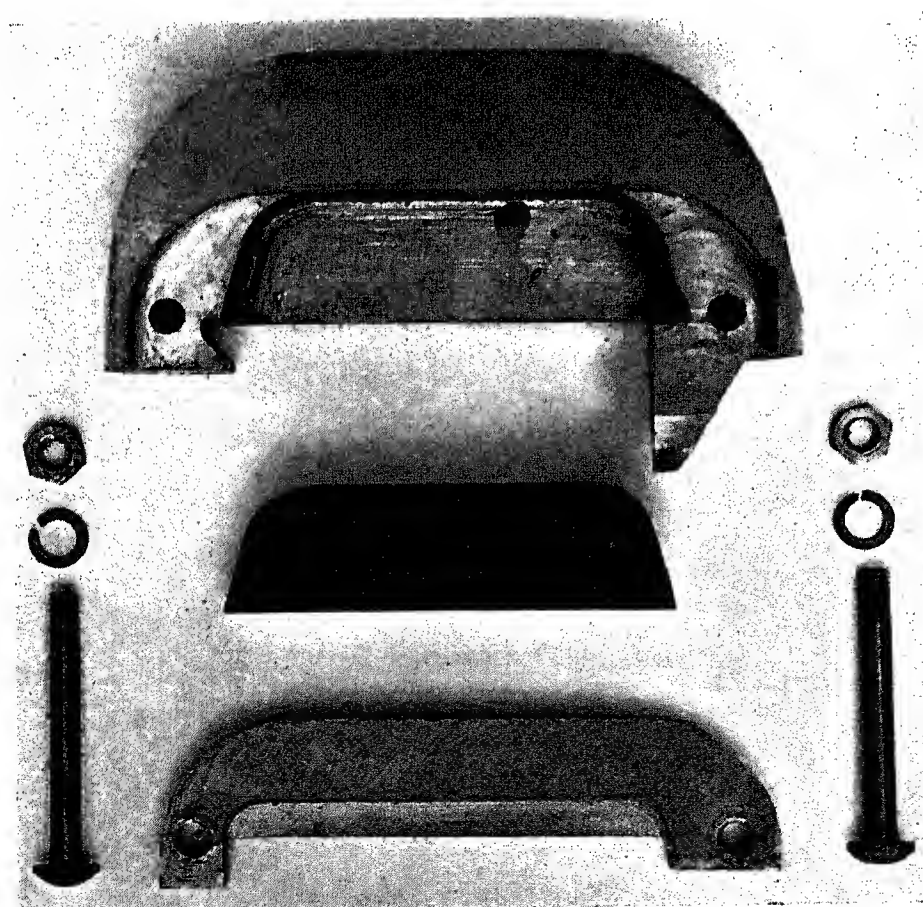


Fig. 12.—View of carbon current-collector.
The side clamping plate ensures good contact.

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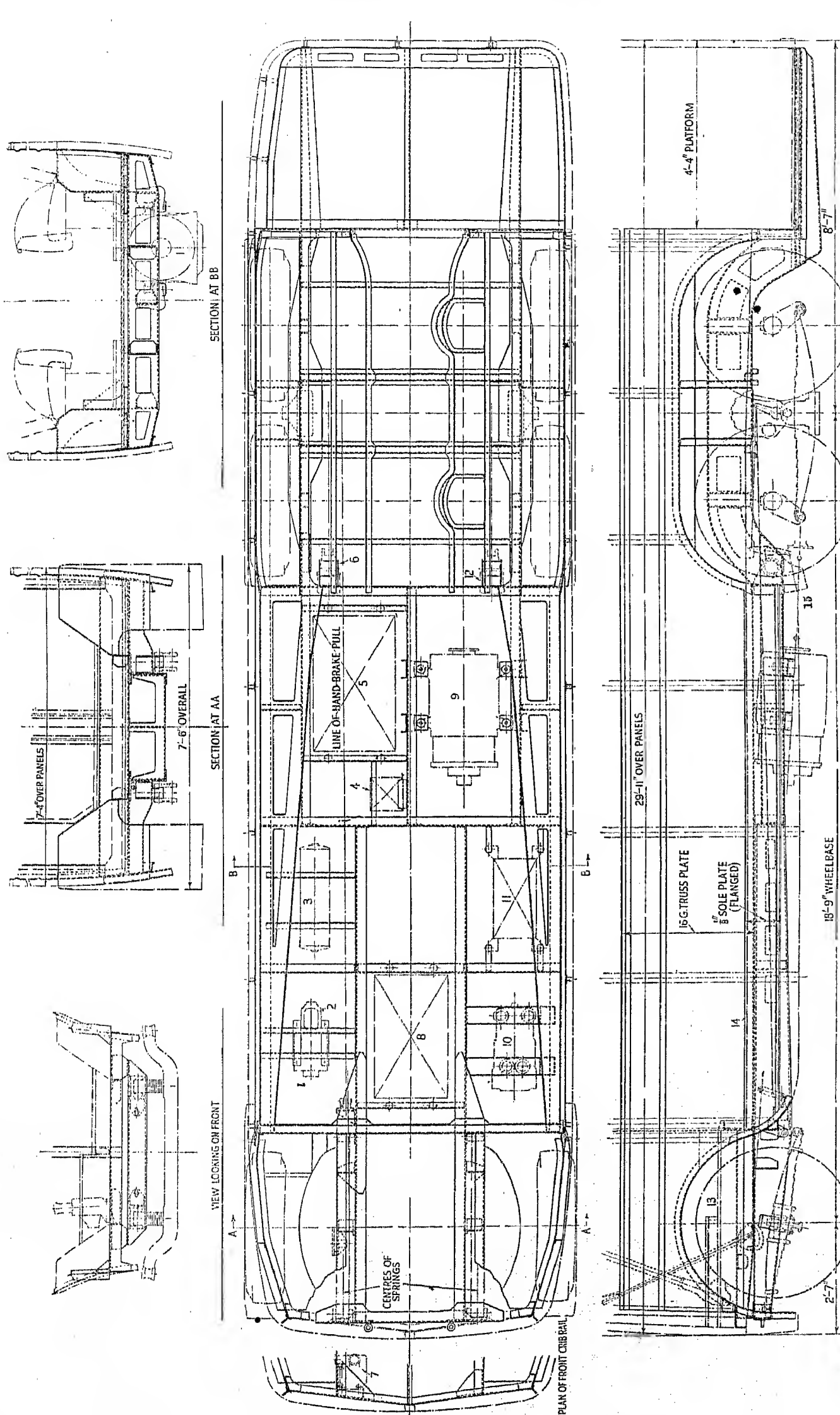


Fig. 9.—Layout of an experimental chassis-less trolleybus recently constructed.

in preference to the half cab, affords the opportunity of departing from the principle of supporting the driver's cab from the top structure to free it from vertical oscillations due to road shocks. With a chassis-less vehicle the design facilitates the building of the front of the body with sufficient weight and strength to make it capable of resisting vibrations. This reduces the structural weight in the girth of the body which is necessary when the front-road shocks are transmitted to the body through the leverage of the front arms anchoring the front springs.

To illustrate this, a bending-moment diagram is given in Fig. 10. It shows in a general manner the stresses set up in a 30-ft. 3-axle trolleybus with seating capacity for 70 passengers, built on the chassis-less principle. Fig. 10(a) refers to a vehicle with a fixed cab front and Fig. 10(b) to a similar vehicle with a free or semi-floating front.

The maximum laden weight of the trolleybus on the road is $13\frac{1}{2}$ tons, with a laden body weight on the springs of 11 tons. The load is taken as being evenly distributed over the length of the vehicle, the figures being for static weight only. It is assumed, for purposes of calculating the stresses on the material, that the framing above the lower deck window-sill has no strength value. The body load is taken by the lower deck truss-plate and solebar and rear-wheel arches; in the case of the fixed cab front the load is shared by the front-arm members of the under-frame. A comparison of the two diagrams shows that a trolleybus built without using as strength members the portion of the longitudinal arms projecting beyond the bulkhead introduces a number of body stresses which are not encountered on a body with a fixed front.

CURRENT COLLECTION

The Wheel

The wheel as used for current collection is less suitable for trolleybus operation than the sliding carbon collector. The wheel revolves on a horizontal axis which is free to rotate about a vertical axis. Fig. 11 shows the

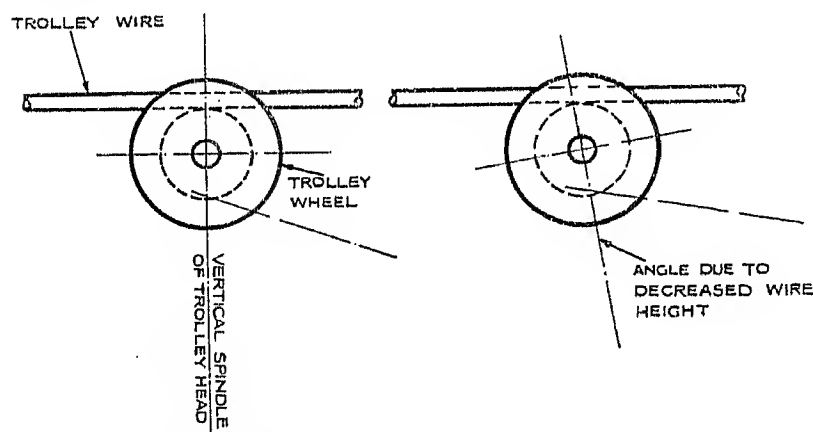


Fig. 11.—Diagram showing the effect of decreased wire height on the angle of the trolley-head spindle to the wire.

extreme angles which the vertical spindle takes with the maximum and minimum wire height. The gyrostatic action of the wheel, and the inclination of the spindle to the vertical which produces frictional resistance, impede the free motion of the wheel from responding to change of direction. This is an important factor when the vehicle is passing through special work in the

overhead line at junctions, as under these conditions the safe rate of change of direction is limited.

The instantaneous centre of rotation of a wheel on the wire is a point. This restricts the design of overhead fittings, as the length of guide at frogs and crossings is limited and the minimum angle of the fittings which can be used is 25° . The greater the angle on these fittings the more uneven the change of direction of the head and, with the revolving wheel, the greater the resistance to change.

The Sliding Carbon

Certain mechanical advantages, coupled with quietness of operation, are associated with what is termed "shoe collection" of current. The longitudinal line of carbon contact with the wire, the absence of rotational inertia, and the length of guide at frogs and crossings, allow for better operation and improvements in overhead fittings. The carbon type of collector is shown in Fig. 12 (see Plate).

In trolleybus operation, intersections of overhead lines are comparatively frequent, and this necessitates numerous overhead fittings and an interruption from the running wire to a metal or insulated runner. The carbon holder has been so designed as to protect the carbon from impact at these fittings. This is accomplished by providing holders with a suitable profile and by making the fittings to angles of 65° . The change-over from the condition where the carbon is running on the wire to where it is passing over the fittings on the angled faces of the holder, forces the shoe downwards until the carbon is free of the metal or insulated sections. The 65° angled section of the holder only comes into action at special work on the overhead line, as normally the carbon bears on the wire and the vertical walls of the holder retain it in position. The vertical displacement of the holder when entering the fittings occurs in rapid succession at junctions, as the fittings are usually located adjacent to each other. The impact which occurs between the holder and the ramp on the overhead fittings causes a downward pressure, in addition to which the frictional drag of the head when the trolley boom is not tangential to the wire sets up a downward force, all acting against the total upward trolley-boom spring pressure of 35 lb.

Reaction to these downward forces is provided by fitting a hydraulic shock-absorber to the trolley base which damps the downward movement of the boom whilst allowing free upward swing to meet the varying heights of wire. This one-way shock absorber enables the trolley boom to store momentarily the energy given out by the impact of the holder on the fittings and to maintain the upward pressure of the springs, thus preventing the head from reaching a state of equilibrium, when a de-wirement would take place. The absorber has the effect of damping any oscillations which may arise from the road surface or from the elasticity of the boom. Fig. 13 illustrates the snubbing device.

The results will now be given of the laboratory and service electrical tests undertaken to decide the quality of carbons necessary for the varying climatic conditions under which current collection takes place. The blocks are formed by baking at a high temperature a mixture of reasonably pure amorphous carbon with oil or tar as the

binding medium. The grade of carbon which has given the most satisfactory results is a very hard close-grain amorphous variety, rather than graphitic. Analysis of this material shows that it contains 94.8 per cent carbon. The main constituents of the ash content (expressed as percentages) are:—

Acid-insoluble portion (mainly silica) ..	39.4
Ferric oxide	42.5
Calcium oxide	3.5
Aluminium oxide	2.6
Sodium, magnesium, copper, and acid particles	12.0

The varying life of carbons in service gave cause for further investigation. In dry weather over 1 000 miles can be taken as an average, whereas under wet conditions the mileage varies between 400 and 600 miles. The

The current and voltage on striking a short arc (about 0.5 mm.) were the same under water as in air; the current increased rapidly in air as the electrodes became red hot, while under water the current remained steady. Table 1 gives the relative amounts of energy in the arc with the carbon under water and, alternatively, dry.

Table 1

Conditions	Direction of current	Length of arc	Voltage across arc	Current
		mm.	volts	amp.
Wet	Copper to carbon	0.3	18.20	60-50
Dry	do.	0.3	13	50
Wet	Carbon to copper	0.8	30.35	50-45
Dry	do.	0.8	23	50

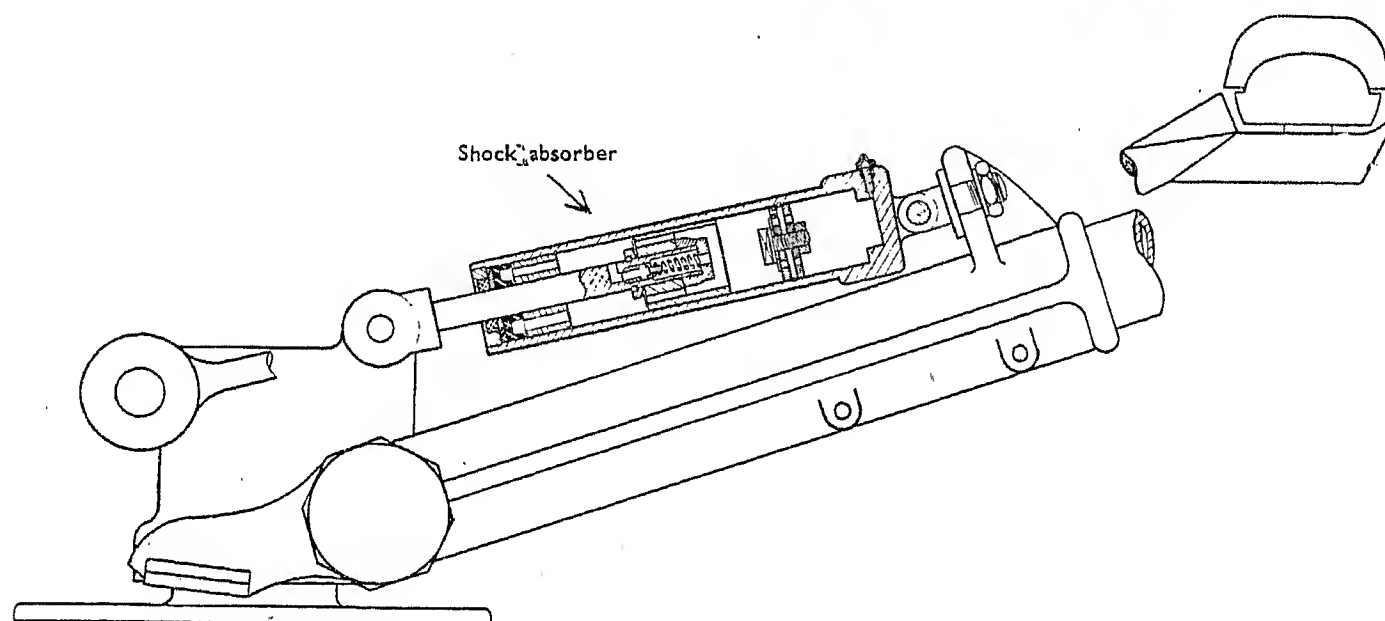


Fig. 13.—The arrangement which is used to decrease the number of trolley de-wirements: a hydraulic shock absorber acting in the downward direction only.

research was split up into six series, namely: (a) Electrolytic. (b) Arcing. (c) Running tests with trolley wire fitted as rings on a drum. (d) Running tests with reciprocating motion (arcing). (e) Running tests with reciprocating motion (no arcing). (f) Running tests with reciprocating motion and with special grades of carbon.

(a) The electrolytic tests were carried out with current passing between the carbon and the copper wire in contact under water. At 35 lb. total pressure between the carbon and wire the voltage-drop was insufficient to give any appreciable electrolytic action. The pressure was varied down to 5 lb., when the resistance increased with time until electrolysis of the water commenced with the increased voltage. This occurred only at the points of contact between the carbon and the wire, and probably would not have happened had there been any relative motion. The conclusion drawn was that the excessive carbon wear experienced during wet weather was not due to a true electrolytic effect.

(b) It was found, with tests taken at 110 volts with ballast resistance, that the arc could be maintained under water between the copper wire and the carbon for a much shorter time than in air. There was a transfer of material across the arc without disintegration of the material.

A much greater amount of energy is absorbed in the arc when the carbon is under water. In the dry arcing tests the carbon became red hot and the surface became partially converted to artificial graphite.

(c) Two rings of standard trolley-wire were fitted as slip-rings on a cast-iron drum, which was rotated by a variable-speed motor. The current flowed from two carbon brushes to the wire; the arrangement being a machine modified for the purpose, it was possible to use only reduced-size carbons. The tests showed practically no wear on a wet wire with 100 amperes passing and with 40 lb. total pressure on the carbons, but wear occurred when the pressure was lowered to 16 lb. The tests were inconclusive, as the small diameter of the drum restricted the scope of the experiment. It indicated, however, that a lower contact pressure between the wire and the carbon reduced the life of the latter.

(d) The reciprocating tests were most successful in reproducing the condition of carbons collecting current from a wet wire. A piece of trolley wire was mounted in an apparatus and given a reciprocating motion across two full-sized carbon inserts, with a current of 130 amperes passing between the two blocks and the wire. The current was broken alternately at the ends of the

stroke, which resembled the trolley head passing over special work in service. The tests proved that although visible arcing is less under wet conditions, the rate of wear is approximately 4 times that under dry conditions, and the carbon surfaces are less polished.

In London the use of carbons is general on a fleet of over 1 700 trolleybuses. A grade of carbon is used which has the mechanical properties required to provide a reasonable life under the frictional and current-collecting service to which it is subjected.

The experiments described and the tests carried out in

trolleybuses passing over the line. The heaviest service of 13 000 vehicles traversing the wire per week necessitates wire lubrication every 7 days, whereas less intensive services only require lubrication at 3-weekly intervals. Where side running is excessive, and generally at road-excavation work, the lubrication of the wire is carried out still more frequently, and receives close attention. The object is to obtain on the wire a highly burnished surface so that negligible wire wear takes place.

The lubricant from which the best results have been obtained is made to the following analysis: Graphite

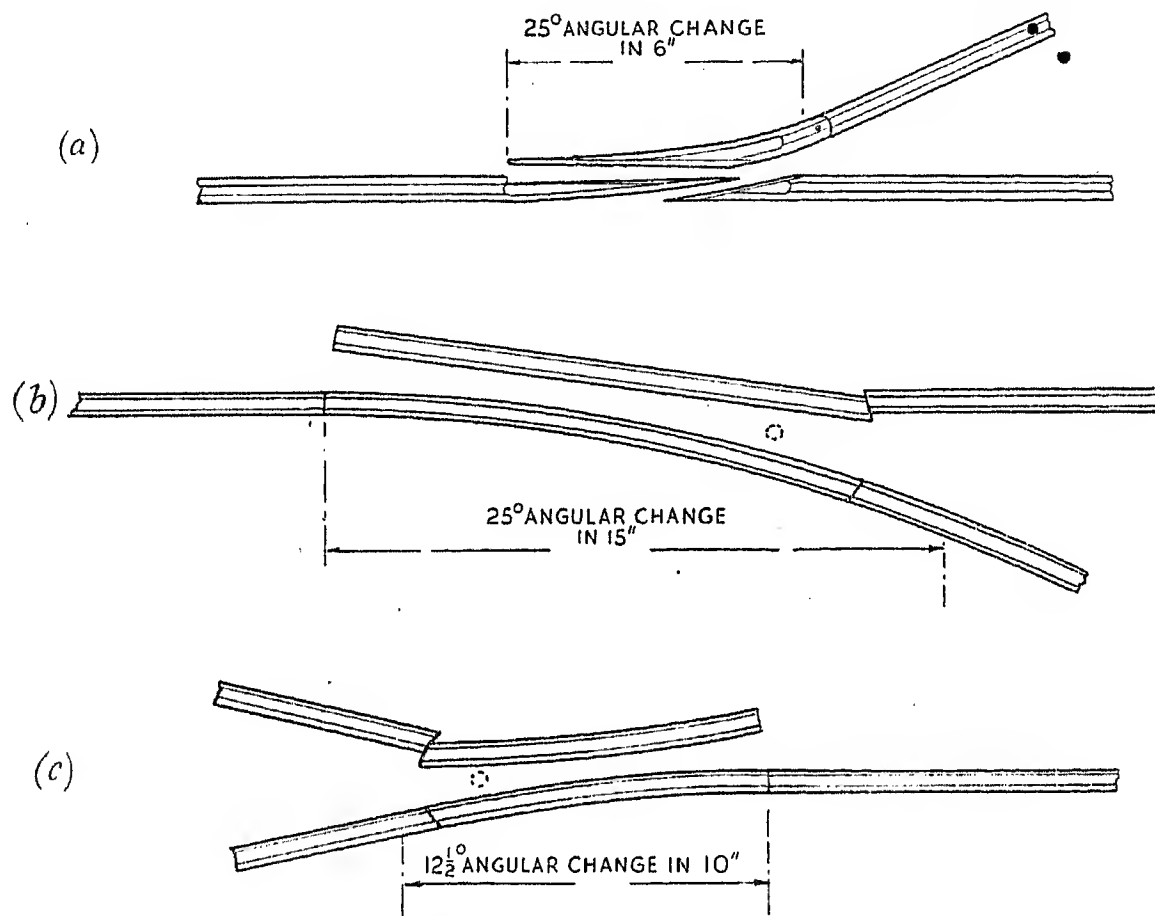


Fig. 14.—Overhead fittings.

- (a) Original-type single-tongue frog, 25°.
- (b) Double-tongue frog without gaps on straight; with large-radius curved tongue, 25°.
- (c) Double-tongue Y frog; with large-radius curved tongues, giving a total angular change of direction of 25° (a new development).

service have proved that electrolytic action does not play an important part in producing rapid wear, and this is supported by observations showing no marked difference between positive and negative carbons. In dry weather when arcing occurs the heat generated at the surface is sufficient to graphitize the surface film, which helps the carbon to resist the burning action. In wet weather the water prevents the carbon from reaching a sufficiently high temperature to become graphitized on the surface; hence the greatly increased wear.

Wire Lubrication

The success of carbon collection depends to a large extent on the lubrication of the wire. Experiments have been made with a graphitic carbon block, but the amount of graphite transferred to the wire was very limited irrespective of the pressure or speed of application. A special lubricating vehicle is used in London, equipped with a gantry supporting two lubricating heads. The frequency of lubrication is related to the number of

(powdered), 25 lb.; gum solution, 28 lb.; trichlorethylene, 25 lb.; petroleum spirit (X3), 24 lb. The graphite powder possesses an ash content of 17 per cent. The gum solution is of a modified coumarin-type synthetic resin in trichlorethylene, in the proportions of 3½ lb. of modified resin to 10 lb. of trichlorethylene. The petroleum spirit known as X3 spirit is a close-cut distillate of specific gravity approximately 0.79 and a boiling range of 110°–120° C. This lubricant cannot be applied to a wet wire; but it has the property of quick drying, which allows the wire to be lubricated without interrupting the services.

Overhead Construction

The present-day practice is to employ a tight wire, in order to provide smooth running. The conductor wire is tensioned up to 1 500 lb., whilst the span-wire tension is in the neighbourhood of 800 lb. The tendency in the design of overhead fittings has been to decrease the angles at frogs and crossings and to substitute insulated steel spacing bars for the wooden beams at insulated crossings.

Where a junction or turn-out is made, a frog is required. When the direction of motion of the vehicle is towards the frog to the single wire, a trailing frog is used. The angle of the trailing frog with a carbon holder as illustrated can be as small as 8° , as the fixed gap with this angle does not exceed the length of the holder.

When the vehicle approaches a turn-out a leading frog is used, which necessitates incorporating a movable tongue. The mechanism to provide the movement of the long Y-type double tongue gives a reliable action and permits of an angle of $12\frac{1}{2}^\circ$ (see Fig. 14). The latter provides an easier movement to the change of direction of the head than the designs previously used. The electrical operation of these frogs is by means of a push-button solenoid and is carried out by the conductor of the vehicle. The push button is fixed to a pole a convenient distance from the frog, and a signal light in a lantern shows the position at which the frog is set. This lantern is placed at the junction, and the driver reads the signals as motorists read our familiar traffic lights. Should the frog not be set for the route the driver intends

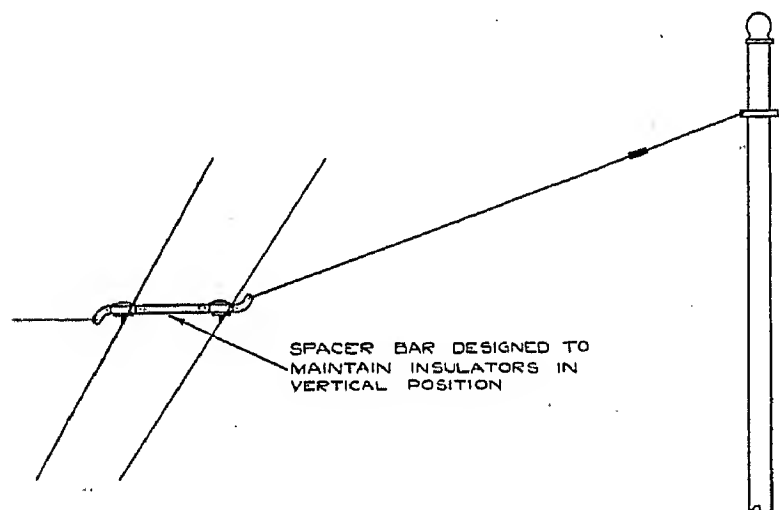


Fig. 15.—Trolley-wire support, for straight line or curves.

to take, the conductor operates the push button, which is located at a stopping place. Where the preponderance of traffic is in one direction the frog is automatically brought to the position to suit the majority of vehicles, thus minimizing the frequency of push-button operation of the frog.

Assuming a trolley wire with the maximum permissible span of 120 ft., the load on the hanger is that due to the dead weight of the wire with the additional load due to ice and windage and the angular change in direction of the wire. To enable the two wires, which are spaced 2 ft. apart, to be suspended an equal distance from the ground, and to maintain the ears, which grip the wire, vertical, the ends of the hangers and spacer bars are bent in a downward and upward direction respectively, so that the span-wire pull is directed below and above the trolley wire (see Fig. 15).

The wire is so located in relation to the normal path of the trolleybus that the trolley boom is as nearly as possible in line with the wire, usually about 10 ft. from the kerb. At special work, where the head passes through the frogs and crossings the radius of curvature of the fittings is made as great as possible.

Unearthed Overhead Transmission Line

On the system in which the negative side is earthed, the insulation of the overhead line is ascertained by measuring with a milliammeter the current passing at full working voltage from the positive line to earth. On the unearthed system, the insulation is measured by a special instrument which enables the insulation of the cables and overhead lines to be measured at the substation over what is normally 2 miles of routes.

The supply voltage for the purpose of the test can be assumed to be constant. Referring to the circuit diagram shown in Fig. 16, the resistance of the voltmeter used is a constant, R_1 and R_2 are respectively the insulation

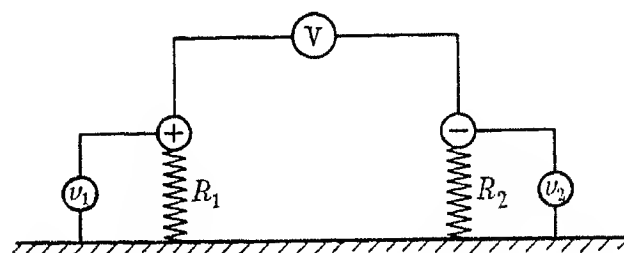


Fig. 16.—Diagram of connections for testing the insulation of the overhead wires on an unearthed system.

V = supply voltage.
 R_1 and R_2 are respectively the insulation resistances of the positive and negative lines to earth.

resistances of the positive and negative lines to earth, and R is the insulation resistance of the two circuits in parallel. The principle applied in the test is based on the formula*

$$R = r \left(\frac{V}{v} - 1 \right)$$

where r is the resistance of voltmeter, V is the supply voltage, and v is the sum of the readings ($v_1 + v_2$) between each pole or wire and earth.

The voltmeter used for the test is specially designed to indicate R . Two readings are taken, which are added together by the instrument.

Representative readings are given in Table 2 of the insulation values in two sections of all-insulated overhead line and cables. "A" refers to a section not feeding

Table 2

INSULATION VALUES OF AN UNEARTHED SECTION OF OVERHEAD LINE

"A"		"B"		"C"	
Insulation	Weather	Insulation	Weather	Insulation	Weather
ohms		ohms		ohms	
500 000	Dry	500 000	Dry	500 000	Dry
90 000	Wet	65 000	Wet	95 000	Wet

a depot (the readings were taken at night, with no vehicle on the line). "B" refers to a section which includes the feeding of a depot and special work in the overhead line with vehicles on the line. "C" refers to the same conditions as "B," but with the depot excluded.

* See F. C. RAPHAEL: "The Localization of Faults in Electric Light and Power Mains" (London, 1916).

In wintry weather, when snow covers the insulators, immediately a thaw sets in the insulation value drops to 12 000 ohms, but quickly advances to normal values. The unearthed system of overhead transmission provides additional safety for trolleybus operation.

THE APPLICATION OF TROLLEYBUSES

It is impossible to consider the use of trolleybuses apart from questions of economics. The questions which seem to require an answer are: (a) In which sphere of transport is the trolleybus applicable? (b) What are the economic circumstances which justify the use of the trolleybus? (c) Do the public like or prefer the trolleybus as a means of transport?

The slum clearances which have taken place in recent years have to some extent checked the tendency for city dwellers to move out to distant suburbs, and have led to the erection of modern flats on the sites of the out-of-date houses. This housing of the people near to the factories and workshops is a move towards better conditions. Fares to and from work are less, and the workers' partial independence of the vagaries of the climate ensures regular attendance at their place of employment.

The stability of the population in industrial areas enables the question of transport to be viewed over a reasonably long period. The case for the trolleybus is most pronounced where the traffic density is high on established routes. The acceleration, braking, and simplicity of control of the trolleybus give the vehicle an advantage which permits of a better road performance than can be obtained from other types of passenger vehicles. In service the number of stops is high where the density of passengers is heavy, a duty cycle singularly suited to the characteristics of the trolleybus. On hilly routes a margin of speed is available, e.g. a 12-ton trolleybus can climb a 1 in 9 gradient at a speed of 20 m.p.h., starting from rest.

The car-mile and the seat-mile basis for costing are used to provide relative costs in the transport industry. Each method has its uses, but neither provides a formula which takes care of all the variables.

The essential difference in the capital structure of a trolleybus system as compared with a system served by self-contained power units lies in the fixed asset of the overhead lines and cables. The apportionment of the charge on this capital on a vehicle-mile basis varies inversely as the frequency of the trolleybus services. The cost of maintenance of the overhead line increases to a limited extent with any increase in the headway. The total cost per trolleybus mile for capital charges and maintenance of overhead lines and cables has been estimated from the Ministry of Transport return and other statistics. The cost per vehicle mile varies from 0.6d. to 1.1d. on headways of 1 minute to 6 minutes, assuming a reasonable life for the equipment and allowance for wear and tear and obsolescence. The standard of maintenance and the method of overhead construction are factors in the cost which differ with each undertaking. In addition to these charges there is a rating charge on trolleybus systems, an assessment which in some instances is fixed as to the value by the respective local authorities. Against these overhead-line costs can be offset the advantages to be obtained from trolleybus operation of

increased carrying capacity, lower vehicle maintenance, and higher schedule speeds.

The regulations governing the construction of vehicles in Britain enable trolleybuses to be built 1 ton heavier than other forms of road passenger vehicles. Trolleybuses with large seating capacities can be designed to suit the traffic requirements with accommodation up to 70 passengers. The cost of maintaining a 70-seater trolleybus is no greater than that of the much smaller 2-axle Diesel bus seating less than 60 passengers. The capital charges on the vehicles, taken over a period of 12 years and assuming similar seating capacities, show little difference between the two types on a mileage basis. The average energy consumption for trolleybuses operating on an intensive service on a comparatively flat route is approximately 2.75 units per car mile, measured at the substation. The price of d.c. energy varies from 0.5d. to 0.8d. per unit, and at the highest figure the cost per ton mile is high when compared with that for the Diesel bus: whereas at 0.5d. per unit the comparison is favourable.

For passenger services in densely populated areas the

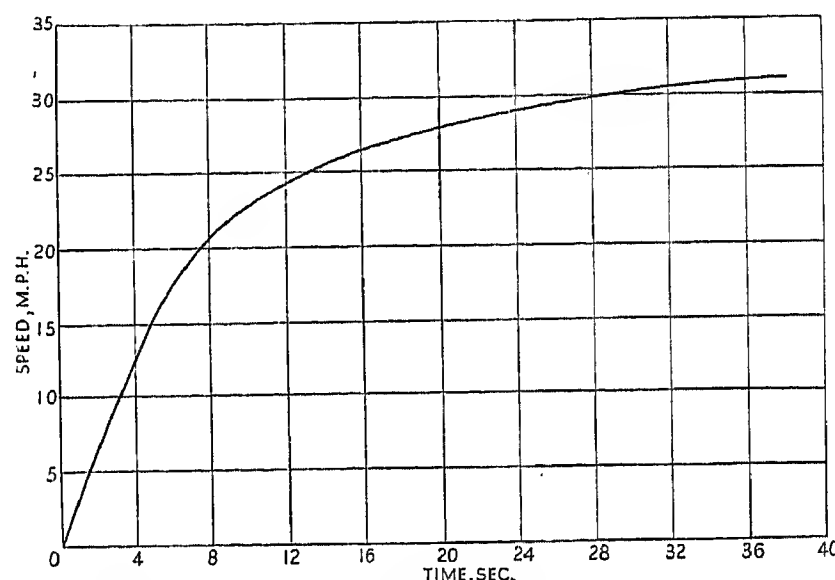


Fig. 17.—Graph showing acceleration of trolleybus.

vehicle with comparable costs which can perform the cycle of stopping and starting to pick up and set down the greatest number of fare-paying passengers in the least time will provide economies. The high acceleration of the trolleybus due to the overload capacity of the motor gives the facility for operating high schedule speeds. In Fig. 17 there is shown graphically the acceleration performance of a trolleybus.

The most severe critics of the trolleybus acknowledge its fine riding qualities and noiseless operation. The ability to marshal vehicles in different areas and the use of non-stop vehicles play little part in the everyday movement of the people to and from work on our roads in our towns and cities. The travelling public have shown their appreciation of the comfort in travel of the trolleybus, as is witnessed by the sustained popularity of the vehicle and the increased volume, in many instances, of week-end and off-peak traffic. The residential population and business people on the routes served by trolleybuses have greatly benefited from the smooth and quiet running of the vehicles.

WRITTEN CONTRIBUTIONS TO THE GENERAL DISCUSSION ON THE ABOVE PAPER

Mr. J. Bentley: The essential difference between the oil-engine bus and the electrically driven trolleybus is the motor and its control; another difference is the necessary alteration to the transmission. The motor, control gear and wiring layout put forward by the author follow lines which are well known for other purposes. The limitations of rheostatic and regenerative braking are those which have been realized in connection with tramcars. In spite of the various modifications which have been put forward from time to time the principal method of braking adopted for tramcars is mechanical.

With the electric-motor-driven bus, mechanical braking presents difficulties due to the fact that the momentum of the combination of the drives includes that of the motor armature. The inertia of the armature is at least equal to that of the bus, and if field range is allowed for, it is increased in proportion.

Any form of electrical braking that depends on a change of the ohmic value of the resistance in the line circuit introduces the risk of non-uniform retardation; also the ohmic value of the resistance must be reduced in steps forming a geometrical progression and at a time rate following the rate of reduction of the momentum, otherwise excessive mechanical and electrical stresses can prevail. The problem therefore is to devise a scheme whereby the rate of change of the ohmic value can be predetermined and taken out of the hands of the operator. As the braking is applied at speeds, and incidentally at values of momentum, which vary in order to obtain the maximum retardation rate for any speed prevailing, the rate of cutting-out of the resistance should be variable.

Electrical braking in the form described is only effective when used in series with the mechanical braking, and only one or the other can be effective at any one time. This is only partially true if the compound-motor method is adopted; the reason being that with this method the back e.m.f. is following closely the line e.m.f., and therefore any change of speed due to the application of the mechanical brake only causes the braking current to fluctuate.

The opposing series method of controlling the braking torque is not often put into practice, owing to the increase of the motor-field I^2R losses entailed. The percentage increase in I^2R loss is such that it will have a large bearing on the design and size of the totally enclosed motor. As the normal field strength is obtained by the combined ampere-turns of the series and shunt winding, the ampere-turns of the shunt winding under the braking condition are those of the shunt winding plus twice those of the series winding. The winding space, or alternatively the temperature rise allowable, has to be increased accordingly.

For a 95-b.h.p. motor operating at 600 volts, the line current will be 130 amperes; assuming that this value gives normal torque, the value of 40 amperes suggested by the author to obtain a retardation of 1 m.p.h. per sec. with the motor as a generator and with the mechanical loss in the gearing, will represent normal torque at the wheels. The retardation given by such a braking torque would appear to be very low.

The oil-engine drive can be used without speed-change gearing by increasing the size of the engine. Both the oil engine and the electric motor at their normal rating exert a fixed torque per revolution, and therefore a reduction in the size of the electric motor would result from the use of a gear-change. By the use of speed-change gearing the inertia of the motor armature is brought to a more reasonable value, and it would appear not unlikely that this method of control might become desirable. If it were adopted the variation of speed required to change one gear ratio to another would only need a small field range, and the brake difficulties—with the mechanical brake due to limited weight for heat absorption and space for adequate cooling surface for heat dissipation; and with the electric brake due to the lack of a method of control which will avoid mechanical stresses—would at least be greatly reduced.

The bus drive as at present proposed is one with two masses of relatively high inertia and with shafting and gearing between. This is an arrangement which in other spheres has proved undesirable. I suggest that it is responsible for the larger worm gear and the difficulties

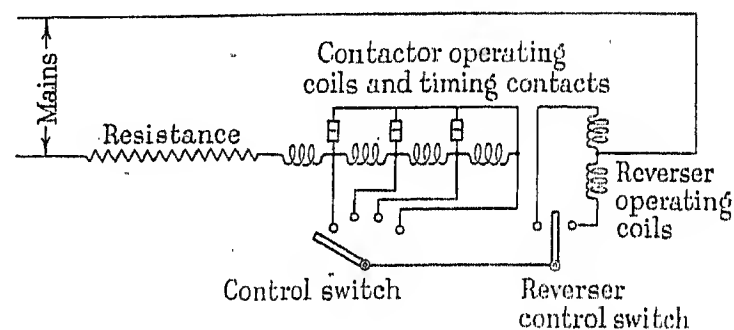


Fig. A

experienced in obtaining a suitable transmission shaft. It would appear to be desirable to introduce into the drive a device to give a small angular slip and thus even out peaks of torsional stress.

Regarding the design of the motor, it would have been of interest to have included in the paper a description of the spider and bearings. Particulars of electrical design would, for instance, have explained why an increase of yoke section should influence interpole efficiency.

The method of insulating the field coils is not one which should be followed without question, and it would be of interest to know the class of insulating varnish used for the asbestos-covered wires. The insulation to earth does not as a rule present any difficulty to manufacturers of motors which are subject to sweating, e.g. motors for marine use. It is largely a question of sealing up the insulation joints so that they do not harbour moisture; and also of providing a breathing device to avoid the dew point when the windings cool down.

The difficulties which the author appears to have met in connection with the design of the contactors can only be attributed to an endeavour to set aside the normal basic principles governing the design of such gear. The use of enamel wire for the coils is usually barred, as oil and other vapours have a detrimental effect on such insulating material. The arrangement of contactor operating coils shown in Fig. A is one which I adopted

in a case where it was necessary to avoid the use of fine-wire windings and their attendant self-induction, namely in the control of winch motors on board ship. The coils are connected in series, with a resistance in circuit across the line, and are inserted into the circuit in rotation. The operating-current range was about 2 to 1. This arrangement gave the extra pull necessary for the first contactors, which required a large break.

One important feature of d.c. contactor design is the necessity of giving a relatively large width between the blow-out checks and plenty of room for the arc to rise vertically with the air current and to clear itself without obstruction. This limits the risk of the arc getting outside the magnetic field of the blow-out coil.

The author states that it is desirable for the reciprocating-type compressor to be run at constant speed, owing to the difficulty in unloading. This design of compressor is of the fixed-displacement-per-revolution type, and therefore it is only the rate of output which varies with the speed, not the pressure.

It would appear that it is necessary for an electric bus to have an earth protection device which, on an earth occurring, will not only open a breaker fitted as close as possible to the point of supply but will short-circuit (by connecting together) the two leads to the motor and control gear.

The curve in Fig. 17 shows an acceleration at starting of 6 ft. per sec. per sec., slowing down at 20 to 25 m.p.h. to 2 ft. per sec. per sec., with a further reduction above these speeds. The acceleration at the start is obtained by a starting current which, with a vehicle stopping and starting frequently, fixes the rating of the motor; while reduction of the rate of acceleration at the higher speeds is due to the difficulty of overcoming the field inertia. This latter limitation was got over for deck winches, which had to compete with the acceleration given by steam winches, by the use of an automatic field diverter; the object of this field diverter being to keep up the torque at a predetermined limit above the normal running torque prevailing at any given moment.

Such a device, which has been successfully applied to many hundreds of winches, was described in my paper published in the *Journal* in 1926.*

Mr. E. H. Croft: The author points out the need for limiting the back tractive effort during rheostatic braking, and the control complication resulting if the series motor be used for braking. I feel it should be made very clear that, if current control be adopted with series motors, the high back tractive effort has to exist to some degree before it is removed by the relay. Thus with such a system the transmission is not really protected. In some equipments using series motors, centrifugal relays control the braking current. This method is much sounder, but any failure is apt to result in a broken transmission. In my opinion, therefore, there is only one solution, namely the compound motor.

The author mentions the benefit derived from limited regeneration combined with normal rheostatic braking, and in this connection I think the use of a compound motor with boosted shunt field should be mentioned. A large number of equipments have been manufactured for services not requiring any appreciable regeneration

but requiring normal electrical braking. By arranging for slight over-excitation of the shunt field during rheostatic braking, a very good braking characteristic can be obtained, while the regenerative characteristic can be limited, even to eliminating regeneration entirely at normal road speeds. This type of equipment has proved very popular for export, and is extremely simple.

I feel that the author's remarks upon contactor design may easily be misunderstood. He states that a clapper contactor has to be designed with a large core to take account of leakage. Actually, if the same design principles are applied to both clapper and plunger contactors, there is little difference in core diameter. The difference in leakage between the two types has little if any effect on the iron sections or ampere-turns. It seems to be suggested that a high flux density is not desirable and is a weakness of the plunger-type contactor; actually, since the pull varies as B^2A , it is easier to get the pull with a plunger than with a clapper. While much can be said for and against both types it is agreed that the clapper may have slight mechanical advantages. I believe that the plunger contactors used by the London Passenger Transport Board are of a special type incorporating certain complicated auxiliary springs; these, of course, are not essential to plunger contactors. Mention is made of connecting discharge resistors in parallel with the operating coil; if these be of such a value that induced surges are materially reduced, they may easily affect the contactor and increase contact and arc-chute wear. In my opinion, therefore, they should never be used. A contactor with a small core diameter will not as a rule be satisfactory. Can the author give data regarding tip and arc-chute wear for the various types of contactor he is using?

Regarding the question of inductive charges due to switching off, I have not experienced this trouble although I have carried out most extensive tests in connection with transient shocks due to capacitance when switching on and off. These are caused by the fact that the motor circuits contain inductance, resistance and capacitance. The slight trouble due to this has been increased since condensers were arranged on the motor for preventing wireless interference. I note that the only condensers used for this purpose by the L.P.T.B. are constantly charged. This is an advantage, as it reduces charging transients. Have the Board carried out any tests on these capacitance transients?

The method adopted for testing is very interesting. The author states that the test is made between conductors and chassis, the secondary insulation being short-circuited; it is therefore clear that that part of the insulation which is more subject to failure due to dirt and splash is not tested daily. The Ministry of Transport requires that the leakage shall not exceed 3 mA when the live parts are alive at 500 volts. The scheme as shown, even with reversed polarity, is not tested under these conditions, as certain portions of the circuits are never energized above half the line voltage. Without the change of polarity the test is, of course, no test, as portions of the circuit are not subjected to any appreciable voltage. In my opinion the daily test should include both primary and secondary insulation and be carried out at full line voltage. It is appreciated that

* *Journal I.E.E.*, 1926, 64, p. 567.

this may present slight difficulties, but suitable methods are available. Regarding the mechanical parts, I agree that the trolleybus has far better riding qualities than any internal-combustion-engine bus, but even so there is room for improvement, particularly in regard to the weight distribution and the stiffness of the front springs. Softer front springs are probably impossible without individual wheel springing, and this may present great difficulties. Correct weight distribution must result in a longer wheelbase and heavier chassis, which at present is ruled out by weight restrictions. I should much appreciate the author's views on this subject.

I note that the supply system is not earthed, and it would seem that a dangerous condition might arise on this account under certain circumstances of atmospheric charging of the lines. Can the author state how this difficulty is overcome?

Mr. W. Gilbert: The scope of the paper is so wide that, no doubt necessarily, description has had to be limited. This unfortunately might give rise to the impression that the methods and devices quoted represent general practice, and that no other satisfactory, or perhaps preferable, solutions are available or in use to-day.

In particular, I would draw attention to the author's comments on the relative merits of rheostatic braking with compound and with series motors. In Fig. 1, Curve B illustrates the typical braking characteristic obtained with a compound motor, while Curve A shows the assumed braking when a series motor is employed in conjunction with a current-limiting relay; it is inferred that braking in the latter case must be very irregular. There is, however, a means of automatically controlling rheostatic braking with series motors which has proved entirely satisfactory and possesses advantages over both systems touched on by the author. In this alternative scheme automatic regulation of rheostatic braking dependent upon the speed of the vehicle is obtained by the use of a multi-contact centrifugal device which governs the field strength of the motor, now acting as a generator. Owing to the high inductance of the field windings and the "build-up" characteristic of the motor the sudden changes of current shown in Fig. 1 do not in fact occur, and experience shows that no irregularity in retardation is perceptible. Moreover, a more favourable shape of characteristic curve can be achieved.

The characteristic shown in Curve C is open to the objection that maximum retarding force coincides with maximum speed and thereby tends to impose excessive strain on the transmission. Further, if retardation at 40 m.p.h. is limited to a safe value, then at 5 m.p.h. braking becomes negligible. This difficulty cannot be satisfactorily overcome by providing two or more notches since this reduces low-speed braking still further, or renders it possible for dangerous conditions to occur at high speeds. By the use of the centrifugal switch operating in the manner described with a series generator a characteristic can be obtained which gives, if desired, lower retarding force at high speed than at low speed, and by cutting out rheostatic resistance on the final notches effective braking can be continued down to almost zero speed.

The author mentions that the rheostatic brake switch

can either be a separate unit, operated by levers from the brake pedal, or can be incorporated in the master controller. There is still another method, employed with considerable success, in which the brake switch is embodied in the foot-brake pedal itself, thus eliminating all the link gear between the pedal and other units.

It is further stated in the paper that the first movement of the brake pedal open-circuits the control and applies the rheostatic brake. Although this is the case on many transport systems it is by no means universal practice, as some operators prefer matters to be so arranged that the driver can hold the bus on an up-grade by means of the foot brake while applying the first power notch, so that there shall be no chance of run-back on releasing the brake. Also, many systems employ automatic current-controlled points in their overhead system, and to operate these it may be necessary to apply power and brake at the same time. To employ the foot brake for this purpose would be impossible if the interlocking were such as is described in the paper.

From the author's description of present-day trolleybus motor practice one obtains the impression that a single-turn armature winding is essential, in the interests of satisfactory commutation. This is by no means the case; there are large numbers of trolleybus motors working in the most arduous conditions both as regards loads and regenerative braking which employ a two-turn winding and give perfect results as regards commutation.

Mr. D. C. Irvine: I am very interested in the author's paragraph dealing with protective relays. It is certainly an advantage to incorporate the over-voltage relay in the vehicle instead of utilizing the over-voltage equipment which is erected in substations. The substation relays are very seldom required to operate, but under modern traffic conditions there may be times when there are no vehicles requiring power yet many that have to use the regenerative brakes. Railways work to a strict timetable, whereas road traffic does not; regenerative braking could be more effectively employed on railways for this reason. Again, on railways there is a continuous load, while in the case of road traffic unwanted stoppages are frequent owing to such things as the signals being against all vehicles on one part of the system at once. Apparatus which only comes into operation occasionally has a tendency to fail on account of unnoticed faults due to such causes as vibration. Plain rheostatic braking combined with pneumatic braking is the most reliable system.

With reference to de-wirement, has the author experienced this on steep turns such as hairpin bends between comparatively narrow roads, when the shoe type of head has been used? To overcome this difficulty I suggest that the shoe should be pivoted slightly forward instead of centrally as shown in Fig. 13: this should assist in re-alignment should the shoe accidentally "nose" on the overhead conductor.

The chief drawback to this suggestion is that the "nosing" tendency would be emphasized should the occasion arise for the vehicle to be reversed; this operation is sometimes necessary, but is by no means usual.

The metadyne system of control has been employed successfully on trains. I should like to ask the author whether this system has been tried with trolleybuses,

and whether there are other objections to it in addition to the space taken up by the metadyne motor.

Mr. C. Johnson: When the compound-wound motor was first introduced on trolleybuses on account of its inherent and simple regenerative characteristics it was claimed that its great advantage lay in the saving of energy rather than in the reduction of wear in the brake linings and drums. It would appear that the saving in energy is now regarded as of little importance, and the rheostatic brake has become the chief electric brake on the vehicle. It would be interesting to know whether any greater importance is attached to this saving of energy now that economy in fuel supplies is being stressed in view of the war.

One disadvantage of the regenerative brake is that its efficient application depends upon the driver and that it is impossible to enforce its use. On the other hand, the rheostatic brake is controlled by the air-brake pedal and its use is automatic and outside the control of the driver. The rheostatic braking of a machine with a compound winding can be designed to give a fairly constant braking effort over a reasonably wide speed-range, but, as the author points out, the braking characteristic can be modified considerably by varying the ratio of shunt to series turns.

Varying opinions have been expressed on the comparative braking characteristics of the differential compound winding and the shunt winding. They both possess the same defect in that the braking acts through the motor gearing and must of necessity be limited to the shock loading capacity of the gearing at high speeds. The maximum braking effort with the compound-wound motor is given in Fig. 1 as 2 600 lb., whilst for the shunt-wound motor it rises to 3 400 lb. at the highest speed. One suspects that the designers would prefer to reduce this latter figure if it were possible to do so without impairing the utility of the brake.

In either case, as the speed of the bus falls, the importance of the electric brake becomes secondary to that of the air brake. What one would like to see is an electric brake with a characteristic resembling that of an air brake, one that would really maintain itself down to a low value of speed. The series motor more nearly possesses this advantage, although it is recognized that there are difficulties in the automatic control of the notches. In view, nevertheless, of the excellent qualities of the plain series motor for acceleration purposes, does the author think this type of motor has received the attention it deserves? Even when a compound-wound motor is used, there is always the attempt to produce on the power side as nearly a series characteristic as is possible. The use of a motor with a strong series winding and a relatively light shunt winding as exemplified in Curve C (Fig. 1) is at best a compromise in its deviation from a plain series characteristic to produce a braking characteristic within the capacity of the motor gearing. The same braking characteristic could be produced with a plain series motor with the field energized from the battery during braking. It would be interesting to know whether this scheme has ever been considered.

Although it is true in theory that the electromagnetic operating systems of clapper-type and plunger-type contactors differ in their ratio of copper to iron, I doubt

whether this could be substantiated by comparing various manufacturers' designs of the two types. Even with one of the given types, the ratio of iron to copper is a preference of the individual designer and is often modified by several factors. It is, however, generally recognized that a clapper-type contactor is simpler in construction than a plunger-type contactor and in consequence should be easier to maintain.

It is only recently that sufficient attention has been paid to the control equipment of a trolleybus. There has been the mistake of regarding the control equipment as an inevitable collection of items scattered about the bus, and the design of the individual piece has borne little relation to the whole. It is now becoming standard practice to mount as much as possible of the control gear in the driver's cab, and this centralization of the equipment is influencing the trend of design. When large fleets of trolleybuses are operated, the question of maintenance becomes of paramount importance and any simplification in the design of the control equipment is a step in the right direction.

The author refers only to electromagnetic control. It would be interesting to know why electro-pneumatic control, which has been so extensively used in other fields of traction, has not been applied to trolleybuses.

One of the advantages of a trolleybus is its capacity for high acceleration, and the tendency is to use this asset to the full. It has been suggested that a system of automatic acceleration is the best means of controlling high rates of acceleration. This would seem to introduce complications in the control gear. Does the author consider that, on balance, the relative simplicity of the modern control equipment outweighs the advantages that would result from the use of automatic forms of control gear which would give various rates of acceleration?

Mr. T. Kearns: The test figures given in the Introduction show the r.m.s. value of the armature current to be 103 amperes. This presumably is the highest r.m.s. figure over a certain period for the run, and not the r.m.s. value for the whole run. I use a figure of 50 amperes per trolleybus as the diversified load maintained at the substation for a heavy service in a flat area; and at the schedule speed of the example, namely 10·79 m.p.h., the kWh per mile per bus are $50 \times 600 / (10 \cdot 79 \times 1\,000) = 2 \cdot 78$, which compares very closely with the value of 2·75 given later in the paper. This means that the diversity factor of the buses, owing to stops, etc., is approximately 2. The average kWh per bus mile over a year for a large industrial city with a flat area are 2·76, again very near to the value (2·75) given. It would be very useful if a typical load curve could be given. What does the author consider to be the maximum permissible voltage drop in a trolleybus system?

A large amount of battery manoeuvring is stated to occur during foggy weather. Is this the normal routine, or a result of accidental de-wirement? In the early days of the trolleybus a device was invented to indicate to the driver the position of the bus in relation to the overhead wires. It consisted of a row of lamps in the cab, actuated by the swing of the trolley arm. It was not adopted extensively owing to the then high cost of lamp maintenance. This objection would not apply

now, and a row of button lamps, or an indicating instrument, installed in the driver's cab, actuated either electrically or by means of a Bowden wire, would be of great assistance to a driver with daylight knowledge of the route, and in a combination of fog and black-out would give a decided advantage over the oil-engine bus.

In the last paragraph of the paper the author implies that the addition of a non-stop service is not possible with a trolleybus system; such facilities might of course be very useful, particularly at peak periods with full duplicate buses to termini. It has always been a matter of wonder to me why the overhead circuit follows tramway practice so closely, for unlike the tram the trolleybus is not limited to rails. The selection of loop lines at stops, junctions of one-way streets, termini, etc., is possible by control from the driver's cab, and perhaps the author would say why such a scheme is not used more extensively. A description of a remote-controlled frog for this purpose was published recently.*

The author's question "Do the public like or prefer the trolleybus?" may be capable of answer in London and a few of the more progressive cities, but in too many instances the appropriate question would be "Do the public know the trolleybus?" Many wholesale conversions of public transport are decided without the citizens having a chance of testing the trolleybus, and once the overhead system has been taken down it is a very difficult matter to get it reinstated for trolleybuses. The oil-engine bus is very mobile and also, from the "management" point of view, very desirable; whilst the public idea of trolleybuses is that of a long line of vehicles held up at rush hours, as were the tramcars. I suggest, therefore, to all intimately concerned with the future of electric transport that the first essential is to educate the public in this matter, in view of the large number of transport undertakings run by public authorities, and naturally subject to the influence of public opinion.

Mr. G. R. S. Prasan (India): In the Introduction the author says that the rating of the motor depends on its duty cycle, including variables such as delays arising from traffic signals, slow-moving traffic, and the condition of the roads. Such variables are difficult to determine. I should like to know whether the motor rating is determined empirically by trial and error or whether there is a quicker method for its determination; for all the variables have to be known in advance in order to design a motor to give a specified speed/time characteristic, and until the motor has been made its characteristic cannot be determined. This seems to be a vicious circle. Further, has any attempt been made to utilize a motor with two commutators and a double-wound armature for series-parallel control, with a view to eliminating the coupling of two motors with different armatures?

Electrical Equipment. No doubt compound motors provide the possibility of regenerative braking, but does the author consider rheostatic braking to be necessary in addition to mechanical brakes? He mentions that the shunt winding consists of asbestos-covered wire; would not enamelled wire serve the purpose? One firm I know have adopted the latter method successfully,

and their motors give a better space ratio than where the former wire is used.

Control Gear. Has the metadyne been considered as an alternative to rheostatic control of speed? Its weight may be an objection, but against this there is a greater saving in rheostatic losses and complete regeneration, thus eliminating rheostatic braking. Moreover, this will reduce delays due to control defects by 5 minutes or more; such delays are serious in heavy traffic.

Battery Operation. Does the installation of a battery, though it helps in emergencies, justify the weight that has to be carried continuously, for without it more passengers could be carried and more revenue earned per bus-mile? I would prefer to make battery-laden trolleybuses the exception rather than the rule, and to use them only where it is difficult to provide turning-circles or turntables to reverse the direction of a bus for its return journey.

Brakes. Will not air-brake operation contribute to noise as at present with trams?

Mechanical Parts. The motor is connected to the driving axles by a short propeller shaft of only 28 in., yet giving low working angles of 2°. This is likely to be exceeded, however, if road conditions are bad. To minimize this danger it is preferable to use a longer shaft, with the motor mounted near the front axles.

Would not a front drive be more efficient than a back drive, although it introduces complications by combining the steering and the drive? The front drive would not only do away with propeller shafts with their universal couplings but also give more headroom on the rear axles, as is evident from German petrol-driven cars.

Chassis-less Trolleybus. This is indeed a development in the right direction in body building, as it is more rigid. The previous types contribute to a good deal of creaking after a couple of years' use. Trolleybus manufacturers would have a market in India if the weight of the bus could be reduced, as the loading capacities on Indian roads are lower than under the conditions prevailing in England.

Current Collection. Sliding carbon is, I consider, a better device to reduce noise, which will be experienced more in residential areas, where the trolleybus is particularly useful for linking the suburbs with the business centres. I should like to know, however, the comparative cost of maintenance with sliding carbon and with its predecessor the wheel.

Overhead Construction. It is contended in India that the necessity of providing turning-circles or turntables precludes the installation of trolleybuses, as the roads are narrow. Will the author state what is the minimum radius of circle required for, say, a 24-seater trolleybus; double-deck buses are out of the question? I feel that on such routes where turning circles are possible the installation of battery-laden buses is a better alternative to the erection of overhead wires. Will the use of sliding carbon entail special overhead fittings; if so, will not the capital cost of the overhead work be increased?

In conclusion, the success of trolleybus operation abroad is keenly watched in India, as that country has absolutely no control over imported liquid fuels but has good possibilities of developing water power and steam power for the generation of electricity.

* *Transport World*, 1939, 85, p. 75.

Mr. F. C. Raphael: From the initial paragraph of the paper I gather that supply to trolleybus lines is standardized at 600 volts (d.c.), and from later observations it appears that, although preference is given to both lines being unearthed, there are some instances in which the negative is permanently earthed. Can the author tell us under what conditions the latter circumstances arise, and whether the negative is earthed solidly or through a limiting resistance? A development of his statement that the unearthed system provides additional safety would also be useful; does this additional safety apply to the overhead conductors and to the current collection or to the vehicles themselves, or does he merely mean greater freedom from electrical breakdown on failure of insulation? It appears to me that one of the main advantages of the unearthed system is that it enables a permanent test of insulation to be maintained during running hours by the method the author employs for his

daily test, or by a simple variation of it. Without this a dead earth on one line would not become apparent until the nightly routine test was made, unless the other line developed a dead earth in the meantime. The choice between earthed and unearthed overhead lines will doubtless depend largely on the source of supply, but where separate generation or conversion is necessary for the trolleybus service it would appear to be worth considering whether a centre-point-earthed system would not be the best of all, thus definitely limiting the voltage of each trolley wire above earth to 300 volts. Earthing could then be done through an ammeter and a limiting resistance, which normally would be short-circuited by a leakage trip as on ordinary 3-wire d.c. systems.

[The author's reply to this discussion will be found on page 246.]

NORTHERN IRELAND SUB-CENTRE, AT BELFAST, 21ST NOVEMBER, 1939

Mr. F. Johnston: While undoubtedly the single-motor drive gives simplicity I should have thought that the 2-motor drive, not necessarily with series-parallel control, would have had such advantages in the event of breakdown that this would have outweighed other considerations.

The author states that asbestos-covered wire is used for the shunt and interpole windings. My own experience with this class of covering, even when impregnated, has not been satisfactory, owing to its liability to absorb moisture. It would be of interest to know how these wires were insulated.

I am amazed at the high temperature rises allowed in the main field, namely 70 deg. C. (126 deg. F.). Lloyd's Rules, which follow the I.E.E. Regulations for the Electrical Equipment of Ships, allow a 63-deg. F. rise for "A" class insulation, in the case of generators and motors on ships, and one cannot go beyond 90 deg. F. even for propulsion work. Even the U.S.A. and Germany would not allow such a high rise as 126 deg. F. Either this figure is very much too high or the allowable marine figures are much too small.

The paper states that the aim is to ensure that the level of the sounds emitted from the motor is less than the level of conversation inside the vehicle. Surely the latter is a very variable quantity; it would have been better to have stated the level aimed at in units of sound.

The point which has interested me most is the risk of shock on trolleybuses. Shock seems to me to be a very real danger, and I am surprised that the Ministry of Transport is satisfied with a daily test, when at any time during the previous 24 hours there may have developed a leak on the system capable of giving a passenger a 600-volt shock from the line or a static charge at 900 volts! In my opinion the first danger should be overcome by installing an earth detector which would show at once when a fault occurred, and a relay which would at once disconnect the system from the line. The latter risk could be minimized by wired or low-insulation tyres. It may be that so far no accidents have arisen from this

cause; but that such will occur when the trolleybus gets old seems pretty certain. Rubber mats and insulated hand-grips can only be regarded as makeshifts.

Mr. F. W. Parkinson: I am pleased to note the precautions taken to guard against the danger of shock to persons boarding or alighting. A failure of insulation during service is bound to occur some time as the equipment ages and deteriorates, and it can be understood that an insulated hand-rail and step provide doubtful protection in wet weather. It would seem, therefore, that the daily examination and tests should be drastic enough to break down any weak spots before the vehicle goes on to the road. These tests should not be less severe than those applied by the manufacturers of the electrical equipment, and should be applied immediately the trolley bus comes off service. The importance of this is easy to realize, as trolleybuses would rapidly lose their popularity with the public after one or two fatal accidents.

Mr. J. S. Scott: Owing to the restricted space, the development of suitable motors must have been a difficult problem. I think that a straight series-wound motor would be a better proposition, as the space factor is very small for a shunt winding at 550 volts, especially with asbestos insulation, which is considerably thicker than fine double-cotton-covered wire. A series winding giving the same maximum excitation would occupy much less space for a similar copper loss, and this saving could be devoted to making a larger armature, which would help the cooling of the machine. The braking problem with a series-wound motor may be got over by using a variable diverter shunted across the field coils and controlled by a contactor, cutting out the diverter at a predetermined overload. I suggest that possibly a better way of cooling the main motor would be by a small separate motor-driven fan which would cool the machine continuously whether running or stationary. I should like to ask the author whether the use of a metadyne has been tried, as such a machine would limit the starting current and would make regenerative braking possible.

[The author's reply to this discussion will be found on page 246.]

THE AUTHOR'S REPLY TO THE DISCUSSION

Mr. G. F. Sinclair (*in reply*): Mr. Bentley suggests the use of an intermediate gear between the driving motor and the back-axle worm drive. This has been successfully used on trolleybus drives but has been excluded from modern designs because the saving in weight due to the use of a lighter motor, by increasing the armature speed, is to a great extent lost by the addition of the reduction gear. Reduction gears require maintenance and, when partly worn, are liable to be very noisy.

Mr. Bentley's assertion, that the troubles with contactors may be attributed to the design not being based on normal principles, can be dismissed. His suggestion of using contactors with the coils in series and a resistance permanently in circuit is not novel and has the disadvantage that, if one coil fails, the control is inoperative. The arc is always taken on one contactor when contactors are connected in series to break a circuit.

If air compressors are driven from a transmission shaft, there is waste of horse-power when the air reservoirs are full and the compressors continue to be driven at the maximum speed.

Field diversion is used on compound motors. The series field can be diverted up to 50 % of its normal strength, thereby giving increased acceleration at trolleybus speeds above 20 m.p.h.

Mr. Croft's communication emphasizes the useful characteristics of the compound motor for trolleybus work. The strength of the shunt field in relation to the series field determines the generator characteristic. The boosted shunt field, and other methods of varying the field excitation, can be successfully employed to modify the motor or dynamo performance curves of the compound machine. It is probably necessary to reduce the regenerative feature of the motor to a minimum in certain circumstances, but in London the principle of providing regenerative control on the accelerator pedal has the advantage of giving an additional brake, for which there is a circumscribed use.

The difference in maintenance between clapper- and plunger-type contactors is only noticeable after a period of use. The plunger contactor develops worn spindles, washers and bushes, and these cause defects which often result in the unit becoming inoperative. The copper replacements are very much greater with the plunger type of contactor, as is also the burning of arc chutes.

The rise in potential due to the circuit being inductive has been measured, and the induced voltage is usually under 500. Such components as the compressor motors and the contactor coils are responsible for the induced voltages. The electric capacitance of each circuit has not been tested separately.

The testing of the secondary insulation nightly would be an added precautionary measure but would be misleading, as the secondary insulation is usually in a vulnerable position and might give low readings although the vehicle would be perfectly roadworthy. Such secondary insulation items are usually of porcelain and are cleaned, when necessary, during the nightly inspection.

The effect of a lightning discharge on an unearthed overhead system presents no greater difficulties than with the earthed system. There is always a limited leakage over the insulators and, with the condensers on the line,

the path to earth for lightning is through the condensers and over the insulators.

I agree with Mr. Gilbert in regard to the design of trolleybus motors. A multi-contact centrifugal device could be so applied as to provide even rheostatic braking with a series motor, but it would be a disadvantage to add to the control gear in order to provide a braking feature which can be accommodated in the motor. Control-gear failures account for a large percentage of the involuntary stops with trolleybuses. Centrifugal relays would make for further complications in the control circuits.

Mr. Irvine suggests an out-of-centre pivot for the trolley heads in order to overcome de-wirements, especially at acute turns. Such a scheme was extensively tried out with trolley heads using wheels. The effect is beneficial when the head leaves the curve to enter the straight, as the action of alignment is quicker. On the straight a wobble is set up which gives rise to de-wirements.

The metadyne could be successfully applied to trolleybuses if weight permitted. The metadyne, besides supplying motor current, could also take the place of the motor-generator supplying the low-voltage lighting circuits.

Mr. Johnson refers to the use of a series motor for driving the trolleybus and to exciting the motor field from the battery for braking purposes. The practice has not been tried on the road but, no doubt, test-bed runs will have been made with such an arrangement. One of the principles in the design of the equipment has been to keep apart high-voltage and low-voltage connections, although this has been sacrificed in the motor-generator. The variation in the condition of the battery would have to be taken into account, but there are no fundamental reasons why battery field-excitation for braking could not be practised.

Control gear designed for automatic acceleration would give a smoother start than that at present obtained. The increase in acceleration obtained from automatic control has proved difficult to take advantage of in traffic. The system which is being tried in London allows for the use of a dash-pot between the power pedal and the master controller and for a current-limit relay in the circuit; the scheme can be termed semi-automatic. Experience may show some marked advantages which will justify the additional control apparatus.

Mr. Kearns gives a figure of 50 amperes per trolleybus as the diversified load maintained at the substation. This value is low, as in London it has been found necessary to calculate the substation capacity on the basis of not less than 100 amperes per trolleybus. Six vehicles fully laden may simultaneously take up to 250 amperes each during acceleration, and this condition has to be met. A $\frac{1}{2}$ -mile section can be overloaded to the extent of the number of vehicles which may, for extraneous traffic reasons, be in the section at any one time. The maximum voltage drop varies with different undertakings. To obtain reasonable vehicle speeds the voltage drop should not exceed 15 %.

With reference to Mr. Prasan's communication, the theoretical characteristics of the services to be operated are plotted. A bus with a self-contained prime-mover

can then be operated over the routes to the desired schedule, when observations can be taken which will show up the traffic features that interrupt the working of the schedule. These features are plotted in the form of a chart by a recorder on the vehicle. The capacity of the motor can be calculated and it is seldom that the calculated characteristics vary greatly from the actual. Motors with two commutators have been tried, but series-parallel control with compound machines is not satisfactory.

Without electric braking on trolleybuses, excessive brake-drum wear is experienced. Enamel-covered wire for the shunt-field windings would not permit of such high temperatures as asbestos-covered wire.

Batteries on trolleybuses are a necessity if road accidents are to be avoided. In the event of an accident the lights are maintained independently of the current supply, thereby avoiding collisions. Battery-manoeuvering is a great advantage on heavy-traffic routes when vehicles may have to be moved from rest from under a dead section or turn short because of some road obstruction.

The rear-axle drive is in its simplest mechanical form when short propeller shafts and worm wheels are used. A front-wheel drive is attractive, inasmuch as lower step heights are obtainable. The incorporation of a motor in each front wheel would overcome transmission problems and was tried many years ago. It is difficult to say whether the duplication of electric motors would result in better operation and maintenance, but the advance in motor design since the early experiments would lead one to think such a front drive would have some limited advantages.

The use of carbons for current collection from the trolley wires requires the overhead fittings to be designed to suit the angle of the carbon holders in order to prevent the carbons from being damaged on entering or leaving the fittings. Compared with trolley-wheel operation the maintenance is less and the wire wear negligible.

The turning-circle required for vehicles is dependent on the speed and the wheelbase. A 24-seater trolleybus with

a 15-ft. wheelbase and 7 ft. 6 in.-gauge front axle would turn in a 50-ft. circle at a speed of 10 m.p.h.

Mr. Raphael's point in regard to earthed systems can be answered when it is considered that many trolleybus systems are linked up with the supply to solidly earthed tramways. The additional safety provided by an un-earthed system is given to passengers and pedestrians. The centre-point-earthed system has been considered. The effect of a fallen wire or of leakage on a vehicle is limited, in the majority of circumstances, to less than 300 volts on an unearthed system.

Mr. Johnston raises the question of the single-motor drive as compared with the use of two motors. The advantage of having an alternative motor in the event of one breaking down is not of great moment, because the electric motor is as reliable as many of the other components of the trolleybus which are not duplicated.

The use of leakage detectors is common on many trolleybus systems. Where the supply system is earthed, these leakage alarms can be used with greater success than on an unearthed system. For recording leakages the device is useful and, used in conjunction with the nightly insulation tests, gives additional information. There is the danger of earths occurring in the leakage alarms, one side of which is connected to the negative wire through a resistance.

Mr. Parkinson suggests that the insulation test should be more rigid in the case of trolleybuses. The design of the vehicles and the disposition of the electrical equipment provides for the necessary precautions against electrical leakage. If the tests and insulation cleaning are regularly carried out, the possibility of shocks to passengers is negligible.

Mr. Scott is of the opinion that a series motor with independent air cooling would be a better proposition than a self-ventilated compound machine. The braking difficulties would not be completely overcome by the use of a variable diverter, and control complications should be avoided. The principle of the metadyne could be satisfactorily applied to trolleybuses but for the weight restrictions.

RESTRIKING-VOLTAGE CHARACTERISTICS UNDER VARIOUS FAULT CONDITIONS AT TYPICAL POINTS ON THE NETWORK OF A LARGE CITY SUPPLY AUTHORITY*

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(Paper first received 29th September, and in final form 27th October, 1939.)

SUMMARY

This report deals with the rates of rise of voltage at the clearance of different types of fault at given points on a network, with the relation between the power-frequency parameters of the various plant units concerned and those effective during the occurrence of the transients of restriking voltage, and with the range of values of rates of rise to be expected at different types of busbar location.

Rates of rise of voltage under different types of fault condition are first expressed in general terms. These are shown to agree with the values measured under different conditions in particular situations on the network of the Birmingham Corporation, by means of the restriking-voltage indicator. The application of the method of symmetrical components to the calculation of transients of restriking voltage on the clearance of all types of fault is discussed, with particular reference to generators. Rates of rise of voltage in concrete instances on an 11-kV system are given, the values ranging from approximately 200 to 7 000 volts per microsecond: it is considered that the latter figure may well represent an upper limit in British practice at this voltage.

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- Appendix I. Clearing of Busbar Faults on a System in which the Neutral Earth Point is Supplied by a Neutral Earthing Reactor.
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- Appendix IV. Note on Effective Reactance of an Alternator so far as Transients of Restriking Voltage are concerned.

(1) INTRODUCTION

There now exists a considerable literature on the subject of transients of restriking voltage (see, for instance, References 1-7, 9, 11, 14, 15), and methods by which such transients may be calculated are now well known. There is, however, a lack of data on the range of rates of rise of voltage likely to be encountered in practice, and on the effective parameters of different types of plant unit which determine the rates of rise of voltage. To fill this gap the E.R.A. has undertaken a survey of restriking-voltage transient conditions at typical sites on British power networks: some of the results obtained from one such system are presented in the present report.

Previous E.R.A. reports on this subject have dealt in some detail with restriking voltages at substations on complicated cable networks,⁴ at substations fed from generating stations by long belted-type cables⁵ and by long single-core cables,⁶ and at substations fed by feeders

* Official communication (Ref. G/T104) from the British Electrical and Allied Industries Research Association.

with step-up and step-down transformers at the generating-station and substation ends respectively.⁷ The present report deals in a more general manner with restriking voltages at various typical positions in a generating station and at substations on a large municipal network.

By the courtesy and with the co-operation of the City of Birmingham Electric Supply Department, the E.R.A. was enabled to take records with the restriking-voltage indicator⁸ (R.V.I.) at typical points on the Birmingham network where it was likely that fairly high rates of rise of voltage would be encountered. The measurements here discussed were made at two major substations and at Prince's generating station, on portions of the system specially isolated and made dead for these measurements.

taken in various locations are used to deduce the effective parameters of individual plant units during transients of restriking voltage under different types of fault condition. In Section (6), the experimental data on the individual plant units are used with Tables 1 and 2 to obtain values for inherent rates of rise of voltage, taking account of the complete network at the various sites at which tests were made. These values are where possible compared with values directly obtained from R.V.I. records taken on the network under similar conditions.

It should be clearly understood that the transients of restriking voltage and rates of rise of voltage referred to in this report are those inherent in the system itself, without reference to the characteristics of the circuit-breaker; that is, the transients are those which would

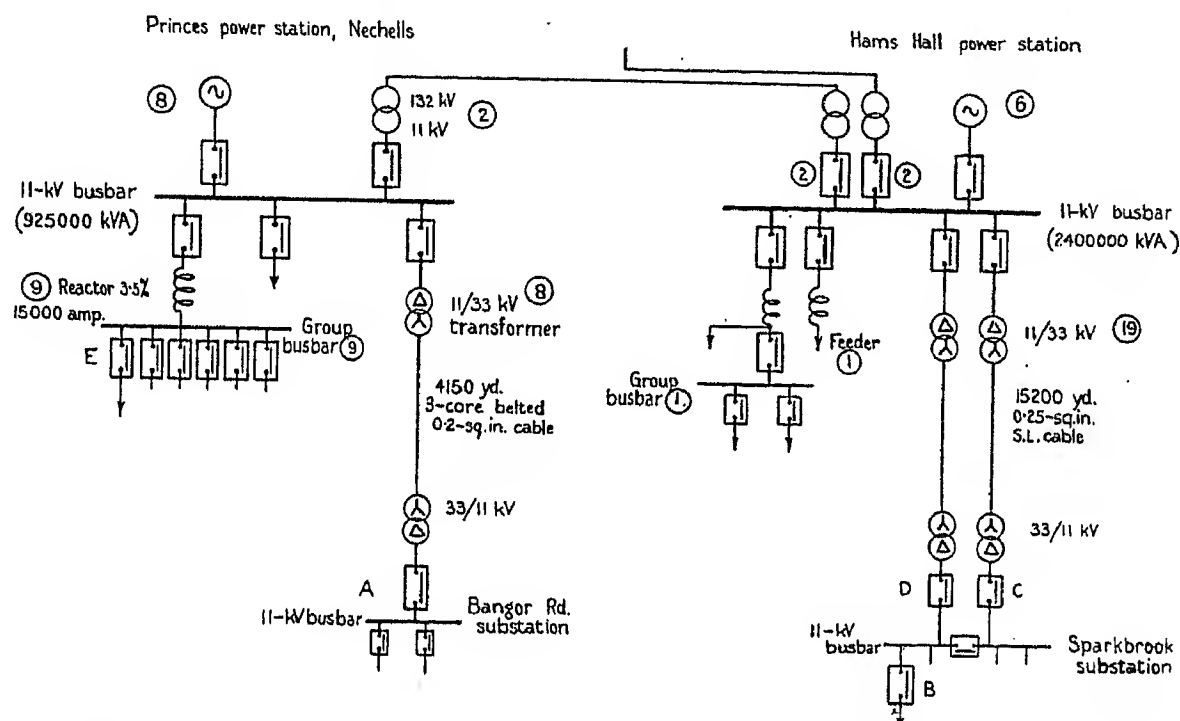


Fig. 1.—Diagram showing relation of points A, B, C, D, etc. (at which measurements were made), to supply on the system.

For precise condition of portion of network where measurements were made, see later Figures. Ringed numbers on plant or station busbars denote number of units of each type on busbars concerned.

Fig. 1 is a schematic diagram showing the relation to the complete system of the points A, B, C, etc., at which the measurements were made. The test points are typical of conditions throughout the system.

The problem of the calculation of rates of rise of voltage at various points on a system consists of three parts: first, the decision as to what particular values of inductance, capacitance and resistance are to be taken as representing each plant unit;* second, how the transients due to these circuit components are to be assembled to represent those due to the system as a whole; and third, the relation between transients of restriking voltage at the clearance of different types (phase-phase, phase-earth, etc.) of fault at a given point.

In the present report, Sections (2) and (3) give a general discussion of the main features of the problem, and contain an attempt to rationalize the subject by arranging the various types of fault in suitable groups for ease of comparison and calculation, as shown in Tables 1 and 2. In Sections (4) and (5), data obtained from R.V.I. records

* A plant unit in this report should be taken to mean a piece of 3-phase apparatus (such as a transformer, feeder, reactor or generator) of a kind indicated by the context.

appear across a hypothetical perfect switch (an α switch)⁹ in which the conductivity is infinite up to the instant of current zero, and zero immediately thereafter. It is further to be understood (unless the contrary is stated in specific instances) that the faults referred to are solid (i.e. have infinite conductivity). Considerations of arc voltage in the circuit-breaker, and fault impedance, introduce further complications not dealt with here.

In this report, the inherent rate of rise of voltage at a given circuit-breaker location for a given type of fault means the rate of rise of voltage across an α switch at that point clearing the fault. The rate of rise of voltage is measured by the slope of the tangent from the origin of the transient of restriking voltage, to the rising curve, as shown in Fig. 14(a) (Plate 2).

(2) GENERAL ASSOCIATION OF HIGHEST RATE OF RISE ON A GIVEN BUSBAR, WITH ABNORMAL REDUCTION IN NUMBER OF OUTGOING FEEDERS

The "highest" rates of rise of voltage discussed in the present report will only appear when the specified faults

Table 1

RATE OF RISE, AND FIRST PEAK, OF RESTRIKING VOLTAGE PER KILO-AMPERE FAULT CURRENT, WITH DIFFERENT TYPES OF FAULT*

1 and 2		3	4	5	6	7	8	9	10	11	12	13	14	15
Item and type of fault		Stage in clearance	See diagram in Fig. 8	Dominant frequency (c./sec.) with earthing by:—		1st peak of restriking voltage is determined by inductance value		Factors relating frequency and inductance of Cols. 5-8 to:—		Rate of rise of restriking voltage (volts per microsec. per kA)†		1st peak of restriking voltage (volts per kA)‡		Number of poles of circuit-breaker across which voltages of Cols. 11-14 appear
				Resistor	Reactor	N.E. by resistor	N.E. by reactor	Rate of rise of restriking voltage	1st peak of restriking voltage	N.E. by resistor	N.E. by reactor	N.E. by resistor	N.E. by reactor	
(a) Earth on supply side														
(i) 3-phase-earth	Phase to phase-earth	(a)		f_0	$0.815f_0$	L	$1.5L$	1.0	1.0	1.0	1.22	1	1.5	1
(ii) 2-phase-earth	Phase to phase-earth	(b)		f_0	$0.57f_0$	L	$2L$	0.63	0.85	1.0	1.26	1	1.7	1
(iii) Phase-earth	Phase to earth	(c)		f_0	f_0, f_1	L	L and L_1	§	§	1.0	$\frac{f_1\omega L_1}{f_0\omega L_0}$	1	$0.5 + (L_1/L_0)$	1
(iv) 3-phase	Phase to phase	(d)		f_0	f_0	1.5	$1.5L$	1.0	1.5	1.5	1.5	1.5	1.5	1
(v) Phase-phase	Phase to phase	(e)		f_0	f_0	$2L$	$2L$	1.0	1.0	2	2	2	2	2
(b) Earth on side remote from supply														
(vi) 3-phase-earth	Phase to phase-earth	(f)		—	$0.815f_0$	—	$1.5L$	1.0	1.0	—	1.22	—	1.5	1
(vii) 2-phase-earth	Unearthed phase	(g)		Largely determined by load conditions. Rates of rise, and first peaks, of restriking voltage will generally be low in these cases										
(viii) Phase-earth	One unearthed phase	(h)		—	f_0	—	$1.5L$	1.0	1.0	—	1.5	—	1.5	1
(ix) 3-phase	Phase to phase			—	f_0	—	$2L$	1.0	1.0	—	2	—	2	2
(x) Phase-phase	Phase to phase	(k)		—	f_0	—	$2L$	1.0	1.0	—	2	—	2	2

* L = effective star inductance per phase of plant unit nearest fault. C = effective capacitance to earth per phase of conductors between last plant unit and fault (losses neglected). N.E. = neutral earthing. $\omega = 2\pi \times$ power frequency. $f_0 = 1/[2\pi\sqrt{(L_1C_1)}]$. $f_1 = 1/[2\pi\sqrt{(L_1C_1)}]$, where L_1 = effective inductance per phase-to-earth fault current and C_1 = total capacitance to earth beyond terminals of N.E. reactor. \dagger Values of K , K^\ddagger , are included in coefficients of Cols. 11-14. \ddagger The figures in Cols. 11 and 12 are to be multiplied by $0.644 \times 10^{-2}\omega L \times f_0$, and those in Cols. 13 and 14 by $2.828\omega L$. \S It is impossible to generalize as to the ratio f_0/f_1 ; the figures in Cols. 12 and 14 are based on the assumption that f_0 is much greater than f_1 . || These rows refer to first stage of clearance of these types of fault. Second stage of clearance of 3 phase-earth and 2 phase-earth faults is as row (a). Second stage of phase-earth fault is as high-impedance fault between phases.

occur under certain definite and in some cases unusual conditions on the busbar or terminal from which the breaker clearing the fault is finally supplied. This condition usually is that no circuit-breaker other than that carrying and clearing the fault current shall be closed and receiving a supply in parallel with the fault. When this

rise of voltage set out in Table 10(b) every time it clears the type of fault postulated: but breakers on the main busbars will only encounter rates of rise of the order given in Table 10(a), when they operate to clear a fault at a time when there are no other outgoing feeders on the busbars. Similarly, when a breaker on the main

Table 2

RATE OF RISE, AND FIRST PEAK, OF RESTRIKING VOLTAGE FOR DIFFERENT TYPES OF FAULT*

1 and 2	3	4	5	6	7	8	9	10
Item and type of fault	Stage in clearance	See diagram in Fig. 8	Fault current cleared, kilo-amperes†	Rate of rise of restriking voltage (volts per microsec.)‡		First peak of restriking voltage (volts)‡		Number of poles of circuit-breaker across which voltages of Cols. 6-9 appear
				Neutral earthing by resistor	Neutral earthing by reactor	Neutral earthing by resistor	Neutral earthing by reactor	

(a) Earth on supply side

(i) 3-phase-earth	Phase to phase-earth	(a)	1	1	1.22	1	1.5	1
(ii) 2-phase-earth	Phase to phase-earth	(b)	0.866‡	0.866‡	0.866‡	1.09‡	1.48‡	1
(iii) Phase-earth	Phase to earth	(c)	$3/[2+(Z_0/Z)]$	$3/[2+(Z_0/Z)]$	§	$3/[2+(Z_0/Z)]$		1
(iv) 3-phase	Phase to phase-phase	(d)	1	1.5	1.5	1.5	1.5	1
(v) Phase-phase	Phase to phase	(e)	0.866	1.73	1.73	1.73	1.73	2

(b) Earth on side remote from supply

(vi) 3-phase-earth	Phase to phase-earth	(f)	1	—	1.22	—	1.5	1
(vii) 2-phase-earth	Unearthed phase	(g)	Depends largely on load conditions (see Appendix I)					
(viii) Phase-earth	One unearthed phase	(h)						
(ix) 3-phase	Phase to phase-phase		1	—	1.5	—	1.5	1
(x) Phase-phase	Phase to phase	(k)	0.866	—	1.73	—	1.73	2

* E_p = busbar phase voltage, in kV. Z = positive phase-sequence supply impedance per phase. Z_0 = Zero phase-sequence supply impedance per phase. Other symbols as for Table 1.

† The figures in Col. 5 are to be multiplied by E_p/Z , those in Cols. 6 and 7 by $(E_p/Z) \times 0.644 \times 10^{-2} \omega L f_0$, and those in Cols. 8 and 9 by $(E_p/Z) \times 2.828 \omega L$.

‡ These values are upper limits. Usually in a 2 phase-earth fault, the fault current in the first phase to clear will be slightly less than $(\sqrt{3}/2) \times$ (3-phase fault current).

§ Best approximation for this figure is:— $\frac{f_1 \omega L_1}{f_0 \omega L} \times \frac{3}{2 + (Z_0/Z)}$

|| Best approximation for this figure is:— $(0.5 + \frac{L_1}{L}) \times \frac{3}{2 + (Z_0/Z)}$

condition is not complied with, the rate of rise of voltage will be considerably reduced. For example, where a feeder a mile long is connected in parallel with the fault, the highest rates of rise of voltage will be reduced to something of the order of 50 volts per kilo-ampere per microsec. over the first 20-30 microsec., and rates of rise already of that order will be reduced by about one-half.

In certain positions this reduction can never occur; for instance, Switch A of Fig. 9 will encounter the rates of

busbar operates to clear a fault on an outgoing feeder at its terminals, the rates of rise given in Table 15 will only occur if there are no other outgoing feeders on the busbar—a condition which can very rarely arise. Under normal conditions the rates of rise will be quite considerably lower. The circuit-breaker feeding a group busbar, opening on a fault on the group busbar, will, however, always have to handle the rates of rise set out in Table 16.

(3) RELATION OF INDIVIDUAL PLANT UNITS TO THE NETWORK AS A WHOLE

The determination of parameters to represent each individual plant unit in the network is the first problem arising in the estimation of rates of rise of voltage at a given point. This problem can be studied by means of the R.V.I., a typical record from which appears in Fig. 2(a) (see Plate 1, facing page 256). Such records, suitably calibrated, may be analysed by methods such as are shown, for instance, in Reference (7), to obtain suitable parameters for the elements R , L , C , R_1 , of a network such as that of Fig. 3, which will completely represent each phase of the plant unit under investigation so far as transients of restriking voltage are concerned. Once these values are known for any plant unit, the part the latter plays in the transient of restriking voltage can be calculated. R , L , C , and R_1 are special values appropriate to the transient conditions dealt with; they will, of course, usually be related to some of the supply-frequency-operating characteristics of the plant unit under examination, but the relation is not always easy to determine from first principles. It is in many cases also necessary to set up different equivalent networks such as that of Fig. 3, to represent the impedance of the given

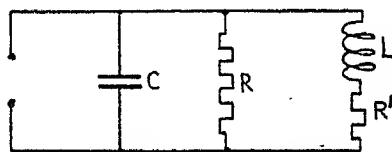


Fig. 3.—Equivalent network representing one phase of most plant units.

plant unit to positive or negative and to zero phase-sequence phenomena.¹⁰

In the present investigation the full analysis of all the records taken on different plant units has not yet been completed. Values have in most cases been obtained for the quantities L and C referred to above, but the resistance (loss) components have not yet been evaluated since this feature is at present under investigation in a detailed study of individual types of plant unit.

It would be a tedious process, and usually unnecessary, to calculate the transient of restriking voltage with reference to the oscillatory characteristics of the whole system from which the fault under examination is supplied. Usually, oscillatory components arising from one or at most two plant units determine the main features of the early portion of the restriking-voltage transient, and the whole supply network operates, so far as these plant units are concerned, mainly to fix the voltage associated with each of these major components of the restriking-voltage transient. If, for instance, as normally happens at a substation fed through one or more transformers, the important part of the transient is determined by the characteristics of the transformers, we can treat the transformers as, in effect, an impedance, giving a rate of rise of voltage of so many volts per microsecond per kilo-ampere of fault current (cf. "recovery impedance").¹¹ The network as a whole determines the fault current at the point considered; when the fault current has been calculated for any given supply and fault condition, the then inherent rate of rise of voltage at the point under

investigation can be calculated by taking the product of the fault current in kilo-amperes and the rate of rise of voltage per kilo-ampere.

It is thus convenient, in studying the restriking-voltage characteristics of various plant units, to obtain for each unit a figure for "rate of rise of voltage, in volts per microsecond per kilo-ampere fault current." It is also convenient to obtain a figure, in volts per kilo-ampere, for the first peak reached in the transient of restriking voltage.

(4) EFFECT OF TYPE OF FAULT CLEARED ON RATE OF RISE OF VOLTAGE

(a) Dominant Oscillation Frequency

One of the main features determining the rate of rise of voltage at a given circuit-breaker is the resonant frequency of the main impedance in the system supplying it. This in many cases varies with the type of fault cleared, even for different types of fault at the same point on a given system. Consider, for instance, the case of the Bangor Road transformers [see Fig. 2(b), Plate 1], assumed, for simplicity, supplied from a generator of zero impedance, situated at the high-voltage terminals. The switch A, clearing faults of different types on the cable between the switch and the 11-kV busbar in the substation, can set up several different frequencies.

A 3-phase-earth fault on the particular type of circuit here considered is cleared in two stages—first one phase, then the other two—the busbars remaining connected to earth after the fault has been cleared. The circuit in which current is interrupted at the clearance of the first phase is as shown in Fig. 4(a). Since the cables between the transformers and the switch are all single-core cables, with sheaths earthed, all the capacitance on these cables is capacitance to earth, the direct interphase capacitance, arising only inside the circuit-breaker and in the transformers themselves, being negligible in comparison. If the equivalent star leakage inductance of the transformers is L per phase, and the capacitance to earth of the cables C per phase, the resonant frequency of the supply network is given by

$$f = \frac{1}{2\pi\sqrt{(C \times 1.5L)}} = 0.815f_0$$

where

$$f_0 = 1/[2\pi\sqrt{(LC)}]$$

At the interruption of the second two phases of a 3-phase-earth fault, the equivalent circuit is as shown in Fig. 4(b). Here the resonant frequency is given by

$$f = \frac{1}{2\pi\sqrt{(2L \times 0.5C)}} = f_0$$

Apart from its influence on the general manner in which certain types of fault are cleared (discussed in Appendix I), the use of neutral-earthing reactors can introduce a third frequency into the phenomenon as follows:—Suppose the neutral-earthing reactor* of Fig. 2(b), Plate 1, removed to the supply side of the switch, the connections being made by very short cables, so that C

* A neutral-earthing reactor may also be known as a neutral-earthing transformer or a neutral-earthing compensator.

is unaltered. This represents the case of a switch on the busbars clearing a fault on an outgoing feeder, no change in the value of C being postulated for the sake of clarity in comparing frequencies. At the clearance of the first phase of a phase-phase-earth fault, the equivalent network is as shown in Fig. 4(c). Replacing the neutral earthing reactor (as is legitimate) by resistance and reactance in series between the neutral point of the equivalent star representing the transformers and earth,

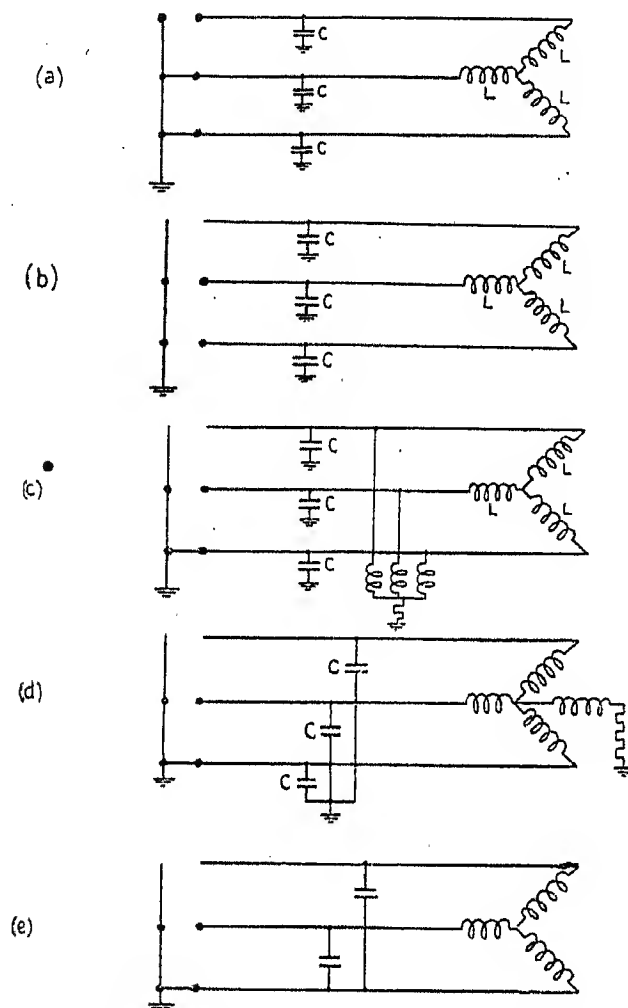


Fig. 4.—Types of fault clearance giving rise to different frequencies on the same network.

Phases shown open and with dotted terminals are those at which rupture is taking place.

- (a) Equivalent circuit at interruption of first phase of 3 phase-earth fault supplied by transformers connected to switch by single-core cable. Resonant frequency $0.815f_0$, where $f_0 = 1/[2\pi\sqrt{LC}]$.
 (b) Equivalent circuit at interruption of 2nd two phases of 3 phase-earth fault supplied by transformers as above. Resonant frequency f_0 .
 (c), (d), (e) Successive reductions of equivalent circuits at interruption of first phase to clear of phase-phase-earth fault supplied by transformers as above, and neutral-earthing reactor. Resonant frequencies f_0 and $0.577f_0$.

there follows the circuit of Fig. 4(d), in which the impedance in the star-earth connection is sufficiently high to be disregarded in comparison with the limb of the star in parallel with it. This leaves an equivalent network such as that of Fig. 4(e), which has two resonant frequencies, f_0 and $0.577f_0$, the amplitude of the component associated with the lower frequency being three times that associated with the higher frequency. The higher-frequency term will be fairly rapidly damped out by the finite impedance in the star point-earth connection. Fig. 5, Plate 1, is a typical record showing these two frequencies.

These various frequencies can also be deduced by consideration of the combinations of phase-sequence impedance networks discussed later in the report and

in Appendix II: it is probable, however, that a clearer idea of the phenomena involved is obtained as described above.

(b) Influence of the System beyond the Fault

The highest frequency of those discussed above (i.e. f_0) is the one which, from considerations of the supply circuit alone, should always be operative for faults

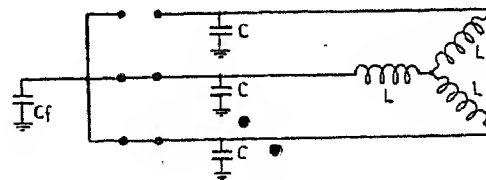


Fig. 6.—Condition of the interruption of the first phase to clear of a 3-phase fault, taking account of the system beyond the fault.

If C_f is large compared with C_1 , resonant frequency $= 0.815f_0$, where $f_0 = 1/[2\pi\sqrt{LC}]$.

involving no connection to earth. In fact, however, for the first phase to clear of a 3-phase short-circuit, for example, the frequency is less than this, by reason of the effect of the system beyond the fault.¹² Conditions at the interruption of the first phase to clear of a 3-phase fault are shown in Fig. 6. If C_f is large, the resonant frequency of the system from the point of view of the phase clearing is $0.815f_0$. In practice it will vary between this figure and f_0 .

(c) Effect of Method of Supplying Neutral Earth

There is quite an important difference between transients of restriking voltage arising at the clearance of the earlier phases of faults to earth, on systems in which the neutral earth is supplied by resistance to the neutral point of three transformers, and on those in

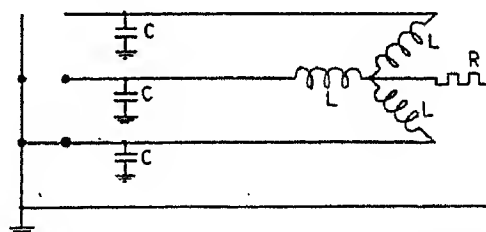


Fig. 7.—Effective circuit at clearance of first phase of phase-phase-earth short-circuit: system with neutral earth supplied by resistance to star point.

which the neutral connection is supplied by a neutral-earthing reactor. Consider the case, for instance, of the first phase to clear of a phase-phase-earth short-circuit. In the case where the neutral earth is supplied through a resistor, the effective circuit at the clearance of the first phase is as shown in Fig. 7. Here the inductance of the remaining phase is, so far as the transient of restriking voltage is concerned, substantially short-circuited by the neutral-earthing resistance, and the resonant frequency of the supply circuit is f_0 . The first peak of the restriking voltage is proportional to the current interrupted and to the inductance L of one phase of the transformer.

In the case where the neutral-earthing reactor supplies the earth point, the effective circuit is as shown in Fig. 7

but with the resistance replaced by an inductance which will in general be quite large compared with L . The case is now that of Fig. 4(e): the restriking-voltage transient will have two frequencies, f_0 and $0.57f_0$, and the first peak of restriking voltage will be proportional to the current interrupted and to an inductance of about $1.7L$.

The distinction between a neutral-earthing resistor and a neutral-earthing reactor is not usually so clear-cut in practice as the above discussion would appear to imply. In general, if two or more star-connected transformers or generators are feeding on to a busbar in parallel, the neutral-earthing resistor is connected to one of them only. The zero phase-sequence reactance is thus higher than the positive or negative phase-sequence reactance, and so even with a "neutral-earthing resistor" it is necessary to insert reactance into the earth branch of Fig. 7 to simulate the network correctly. It is therefore only when a single 3-phase transformer bank consisting of three single-phase units is supplying the busbars that the distinction between the two types of neutral earthing is quite clear: when a single generator or 3-phase transformer is in question, account must be taken of the difference between the positive and zero phase-sequence impedance per phase.

(d) Effect of Side of Switch at which Neutral Earth Point is Provided

Where several supply units are feeding a busbar in parallel, it is usual to earth the neutral point of one only, so that circuit-breakers between the supply plant units and the busbars, clearing on a busbar fault, may operate with the neutral earth connection on the fault side of the switch. In this case the method of opening on faults is different from that which applies when the supply neutral is earthed, the chief difference being that the circuit is always opened in two stages, irrespective of the type of fault cleared, whereas with the neutral earth on the supply side the circuit may be opened in one, two, or three stages according to the type of fault cleared. The point is more fully discussed in Appendix I.

(e) Comparison of Values of Rates of Rise of Voltage, and of First Peaks of Restriking Voltage, for Single Plant Units for Different Types of Fault Cleared

It is now possible to summarize the various rates of rise of voltage encountered on clearing the different types of fault on systems of the general types here considered—that is, systems with neutral earth connection afforded by neutral-earthing resistors and neutral-earthing reactors, connected on the supply and fault side of the switch under investigation. Such a summary appears in Table 1. In this Table, Col. 2 shows the type of fault considered, Col. 3 shows the particular stages in the clearance of the fault, and Col. 4 makes reference to the circuit diagrams of Fig. 8, which show the circuits effectively determining the restriking-voltage transients. Cols. 5 and 6 show the frequencies which determine the restriking-voltage transients, with the neutral earth connection, afforded by star-point resistor and neutral-earthing reactor respectively.

If the frequency of an undamped single-frequency

transient of restriking voltage is f , and the total reactance through which current ceases to flow is ωL , the rate of rise of voltage in volts per microsecond per kilo-ampere fault current is given by $0.644 \times 10^{-2} \omega L f$. This figure is given in Cols. 11 and 12 of Table 1 for single-frequency transients. Where double-frequency transients with the frequencies in known ratio are in question, the rate of rise of voltage per kilo-ampere is in general terms $0.644 \times 10^{-2} k \omega L f$, where k can usually be calculated. These figures also are given in Cols. 11 and 12 for double-frequency transients. In single-frequency transients the first peak of restriking voltage is given by $2.828 \omega L$ volts per kilo-ampere, and for double-frequency transients it is $2.828 k' \omega L$, where k' can again be calculated for a known ratio of frequencies. These figures are tabulated in Cols. 13 and 14.

To obtain the inherent rates of rise of voltage and the peak of restriking voltage under any given fault conditions from single-circuit components, it is now only necessary to calculate the fault currents under the particular fault conditions, and multiply the appropriate figures of Table 1 by the relevant fault current in kilo-amperes.

These fault currents can in general be expressed in terms of the supply voltage and the phase-sequence impedance of the supply system. If we assume that the switch under consideration will clear the fault immediately it occurs, we can write $Z_1 = Z'_1 = Z_2 = Z$,* say. Then if E_p is the supply voltage per phase, and $I = E_p/Z$, the fault currents to earth through the switch for 3-phase, 3 phase-earth, phase-phase, and phase-earth faults are respectively I , I , $0.866I$, and $I \times 3Z/(2Z + Z_0)$, the last figure holding only for the case where the neutral earth point is on the supply side of the switch.

It is not possible to express, in general terms suited to the present discussion, fault currents through the switch per phase in a phase-earth fault with the neutral earth on the fault side of the switch, or in a phase-phase-earth fault. In the former case the fault current will always be quite small in comparison with the other currents here discussed. In the latter case the fault current per phase can be taken as approximately $0.866I$. This holds with the neutral earth on the supply side if Z_0/Z is large: it also holds with the neutral earth on the fault side of the switch, after the small current in the unearthed phase has been cleared.

Using these values we can extend Table 1, as is done in Table 2, to cover inherent rates of rise of voltage, and peak restriking voltage, under different fault conditions. In Table 2, Col. 5 shows the fault current cleared in each stage of clearance, expressed as a multiple of the 3-phase fault current per phase. Cols. 6, 7, 8 and 9 correspond to Cols. 11, 12, 13 and 14 of Table 1, multiplied by the appropriate fault current from Table 2, Col. 5, to give inherent rates of rise and peak voltages under fault conditions.

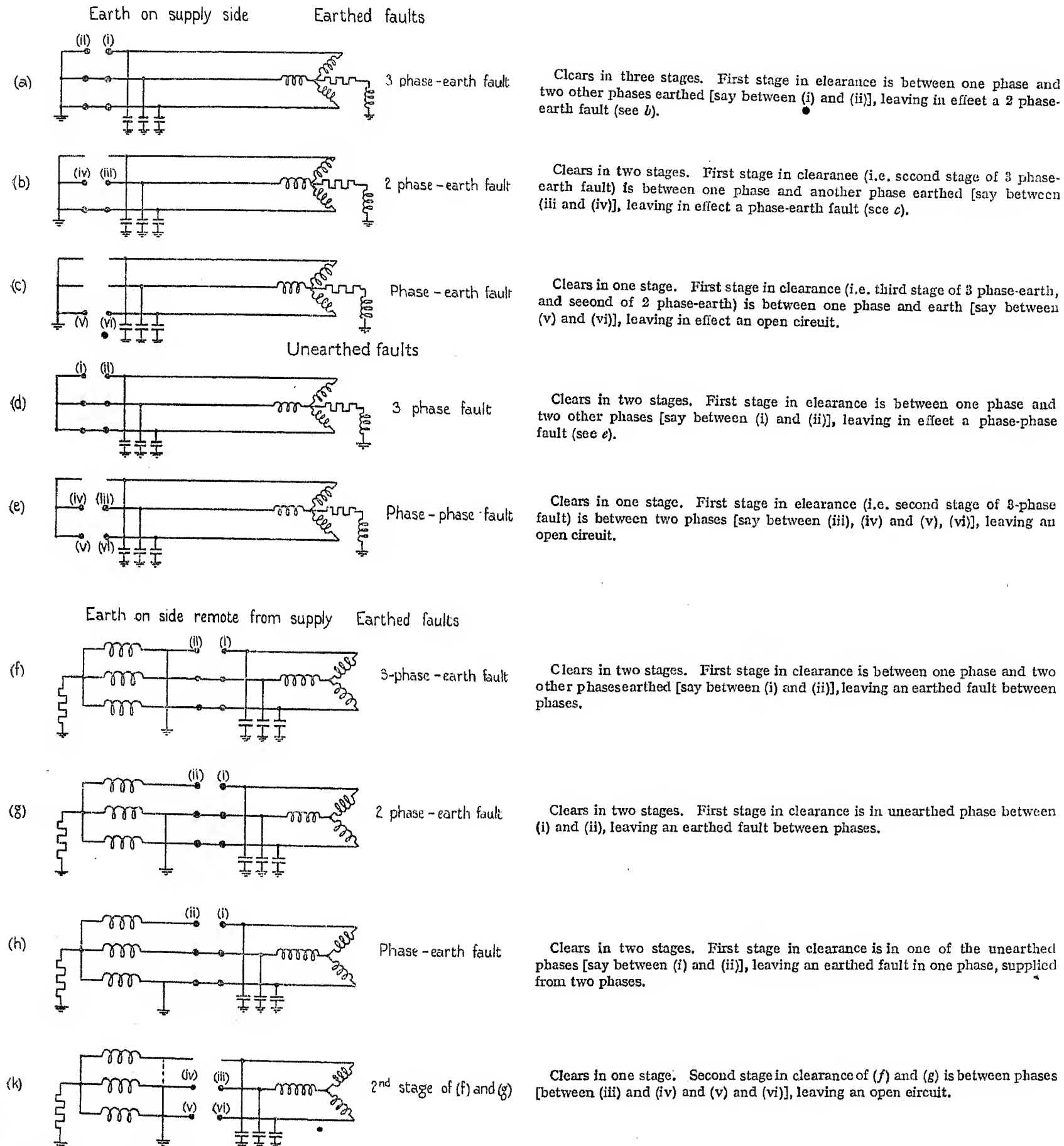
It will be seen that under the circumstances discussed above, the type of clearance giving the highest rate of rise of voltage and peak restriking voltage per pole of the circuit-breaker is the first phase to clear of a 3-phase fault; this is followed closely by the first phase of a 3-

* Z_1 , Z_2 , Z_0 are positive, negative, and zero impedances. Z'_1 = sub-transient value of Z .

phase-earth fault, with neutral-earthing reactor, and then by the first phase to clear of a phase-phase-earth fault with high fault impedance to earth. It should be remembered, however, that per pole of the breaker, the highest *recovery* voltage will occur on clearance of the first phase of the phase-phase-earth fault.

The relations of Table 2 only hold strictly if the breaker

is regarded as opening directly the fault occurs. If this is not the case, i.e. if the rupturing capacity which the breaker is supposed to handle is determined taking account of the demagnetization of the machine during the time the breaker's relays are operating, Z_2 cannot be equated to Z_1 . As time goes on, Z_1 will increase in relation to Z_2 ; that is, the decrement of the 3-phase



Three-phase and phase-phase unearthed faults clear in the same manner as with earth on supply side (see d and e above), except that fault point is earthed instead of supply neutral.

Fig. 8.—Effective circuits at clearance of different types of fault (see Table 1).

fault current will be greater than that of the phase-phase fault current, so that the ratio of single-phase to 3-phase fault current will increase, and the magnitude of the former may even exceed that of the latter after some time. It is thus probable, since the rates of rise of voltage, etc., per kilo-ampere are not affected by these considerations, that the rate of rise of voltage per pole in the first phase to clear of the phase-phase-earth fault will approach, if not exceed, that of the 3-phase fault, and the first peak of restriking voltage in the former case will exceed that in the latter.

(5) EXPERIMENTAL DATA ON EFFECTIVE CIRCUIT PARAMETERS UNDER TRANSIENT CONDITIONS, AND THEIR RELATION TO POWER-FREQUENCY PARAMETERS

(a) Transformers

In the present investigation, records were obtained on three 3-phase transformer groups, one at Bangor Road (point A, Fig. 1) and two at Sparkbrook (point B, Fig. 1). Details of connections in these substations are given in Figs. 9 and 10 respectively. The present section deals only with the characteristics of the transformers themselves and of the cables between the transformer low-voltage windings and the circuit-breaker to the busbars.

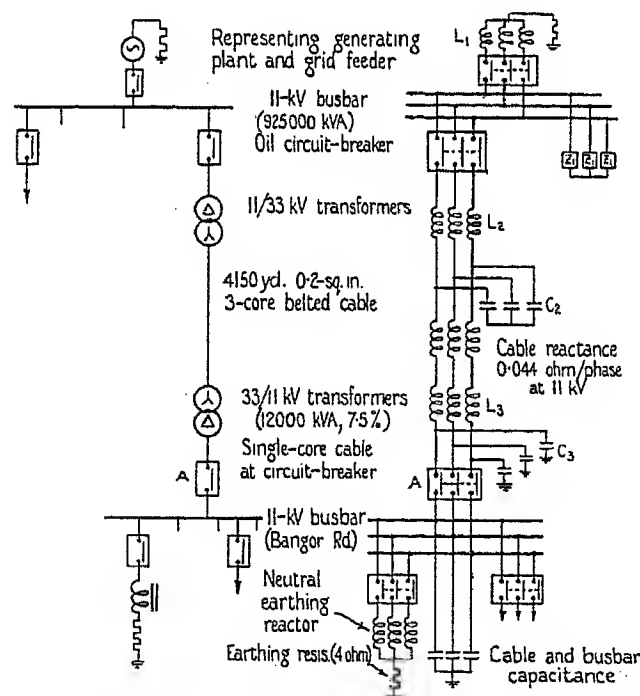


Fig. 9.—Connection to Bangor Road substation.

- (a) Single-line diagram.
 (b) 3-line diagram showing components affecting restriking-voltage transients.
- $L_1 = 0.131 \text{ ohm per phase at } 11 \text{ kV, } 50 \text{ c./s.}$
 $L_2 = 0.731 \text{ ohm per phase at } 11 \text{ kV, } 50 \text{ c./s.}$
 $L_3 = 0.731 \text{ ohm per phase at } 11 \text{ kV, } 50 \text{ c./s.}$
 $C_2 = 0.795 \text{ } \mu\text{F per phase at } 33 \text{ kV.}$
- C_3 { Red phase 71 ft. } 0.5-sq. in. paper-insulated lead-covered
 { White phase 81 ft. } single-core 5-kV cable between trans-
 { Blue phase 91 ft. } former windings and delta point at
 switch; 2 cables per phase. } $= 0.0204 \text{ } \mu\text{F}$
 $= 0.0232 \text{ } \mu\text{F}$
 $= 0.0262 \text{ } \mu\text{F}$

The transformer bank at Bangor Road consists of three single-phase units, each 18.5/10.75 kV, 4 000 kVA, 7.5 % impedance, with primary starred and secondary connected in delta, the delta points being formed at the switch. The two banks at Sparkbrook (Nos. I and II) each comprised three single-phase units, each 18.5/10.75 kV, 6000 kVA, 9 % impedance, similarly connected. The latter two banks were identical except

for the lengths of cable from winding to delta point: even here the difference was not great.

Fig. 2(a), Plate 1, shows an R.V.I. record taken between phase and phase-phase-earth of the Bangor Road transformer, with the neutral-earthing reactor

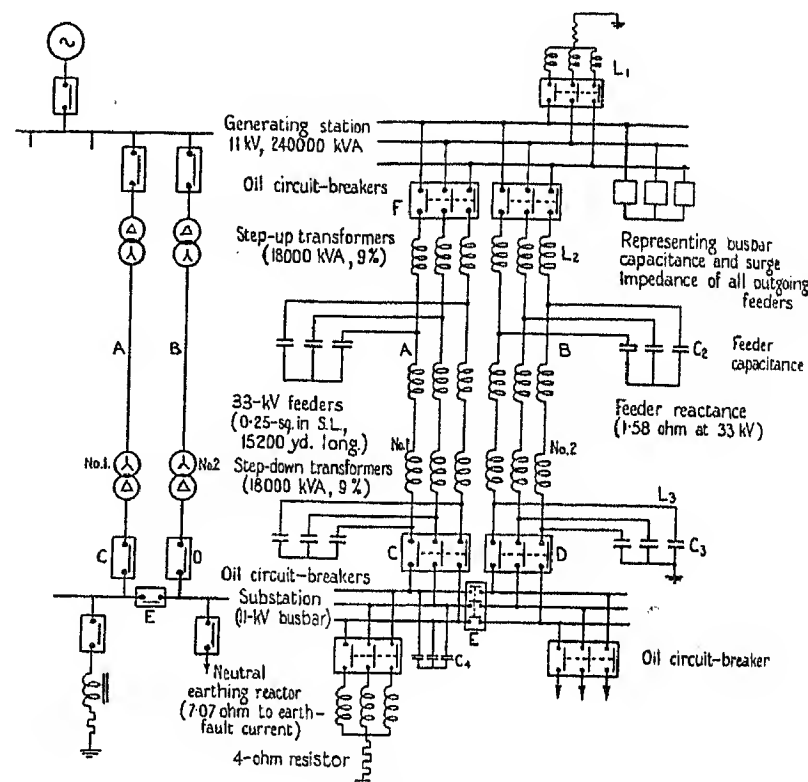


Fig. 10.—Connections to Sparkbrook substation.

- (a) Single-line diagram.
 (b) 3-line diagram showing components affecting restriking-voltage transient.

Feeder A
 $L_1 = 0.050 \text{ } \Omega \text{ per phase at } 50 \text{ c./s.}$
 $L_2 = 0.605 \text{ } \Omega \text{ per phase at } 11 \text{ kV, } 50 \text{ c./s.}$
 $L_3 = 0.605 \text{ } \Omega \text{ per phase at } 11 \text{ kV, } 50 \text{ c./s.}$
 $C_2 = 4.25 \text{ } \mu\text{F per phase at } 33 \text{ kV.}$

Feeder B
 $L_1 = 0.050 \text{ } \Omega \text{ per phase at } 50 \text{ c./s.}$
 $L_2 = 0.605 \text{ } \Omega \text{ per phase at } 11 \text{ kV, } 50 \text{ c./s.}$
 $L_3 = 0.605 \text{ } \Omega \text{ per phase at } 11 \text{ kV, } 50 \text{ c./s.}$
 $C_2 = 4.25 \text{ } \mu\text{F per phase at } 33 \text{ kV.}$

C_3 { Red phase 49 ft. } run of { $= 0.0281 \text{ } \mu\text{F}$ 72 ft. } run of { $= 0.0408 \text{ } \mu\text{F}$
 { White phase 61 ft. } cable* { $= 0.035 \text{ } \mu\text{F}$ 60 ft. } cable* { $= 0.0347 \text{ } \mu\text{F}$
 { Blue phase 73 ft. } cable* { $= 0.042 \text{ } \mu\text{F}$ 72 ft. } cable* { $= 0.0408 \text{ } \mu\text{F}$

C_4 : Whole busbar $= 0.006 \text{ } \mu\text{F per phase.}$

* Four cables per phase between windings and delta point near switch, 0.5-sq. in. paper-insulated lead-covered single-core cable, 5 kV.

connected across it by temporary leads [see Fig. 2(b)] and with the high-voltage windings short-circuited to earth. This record shows the form of the transient of restriking voltage which would arise if the high-voltage side of the transformer were supplied from an infinitely large generator at its terminals, and a switch, located as shown in Fig. 2(b), were operating to clear the first phase of a 3-phase fault. (The "beating" of the high-frequency component of this transient is probably due to asymmetry between the phases of the transformer or between phases of the neutral-earthing reactor, and has not yet been properly accounted for.) Analysis of this record and other similar records obtained on the Bangor Road and Sparkbrook transformers yields the data shown in Table 3. The frequency of the oscillatory term in Fig. 2(a) is of the order of 20 kc./s.: by chance, the frequencies given by all three transformers investigated were of this order.

The data regarding the system constants obtainable from the records of the undertaking were the percentage reactance of the transformers and the capacitance to earth of the single-core cables between the transformer windings and the test point. These figures are given

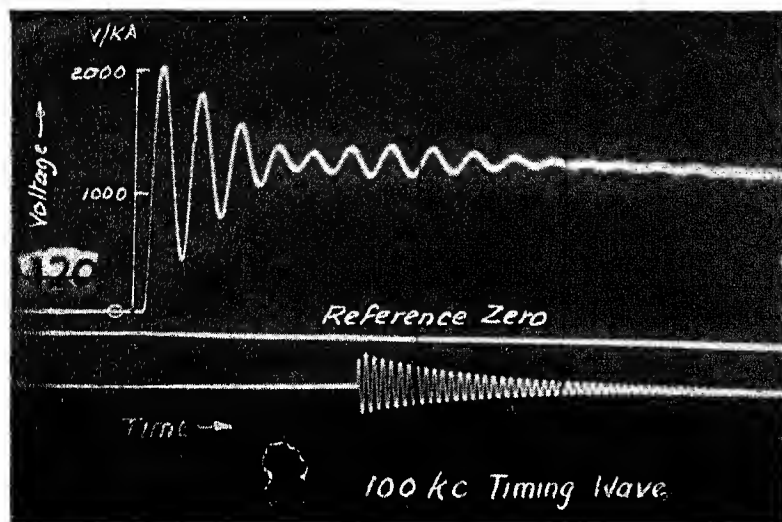


Fig. 2.—Bangor Road substation. Restriking-voltage transient at clearance of first phase of 3 phase-earth busbar fault.

- (a) R.V.I. record of transient of restriking voltage at first phase to clear of 3 phase-earth fault on system of (b).
 (b) System at clearing of first phase of 3 phase-earth fault, assuming supply of zero impedance (for system data, see Fig. 9).

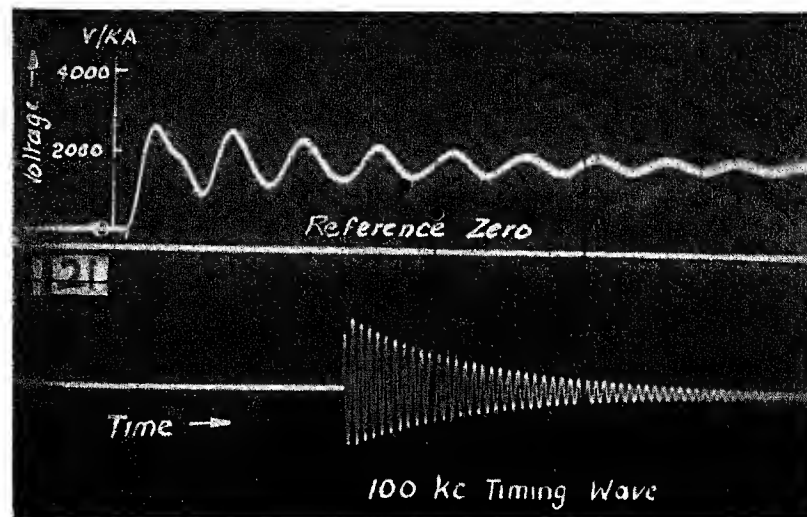


Fig. 5.—Transformers at Bangor Road. R.V.I. record showing transient of restriking voltage at clearance of first phase of phase-phase-earth short-circuit, with supply of zero impedance.

Note the double-frequency transient, referred to in Section 3 (a).

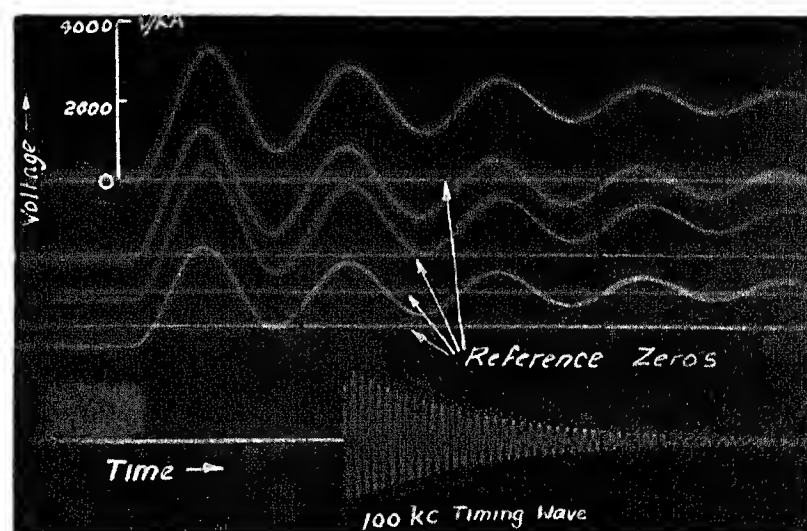


Fig. 11.—11-kV alternator (Princes power station, Nechells): R.V.I. records across 11-kV 23 435-kVA alternator (15.5 % reactance) solidly connected to 174-yd. run of cable, 6 conductors per phase, each conductor 0.5-sq. in. paper-insulated lead-sheathed single-core cable.

Top three records, phase-phase (R-B, B-W, W-R): bottom record, R-(B + W). Neutral solidly earthed in each case: 270 amperes flowing in field circuit, rotor pole axis horizontal during measurements.

GOSLAND: RESTRIKING-VOLTAGE CHARACTERISTICS

Plate 2

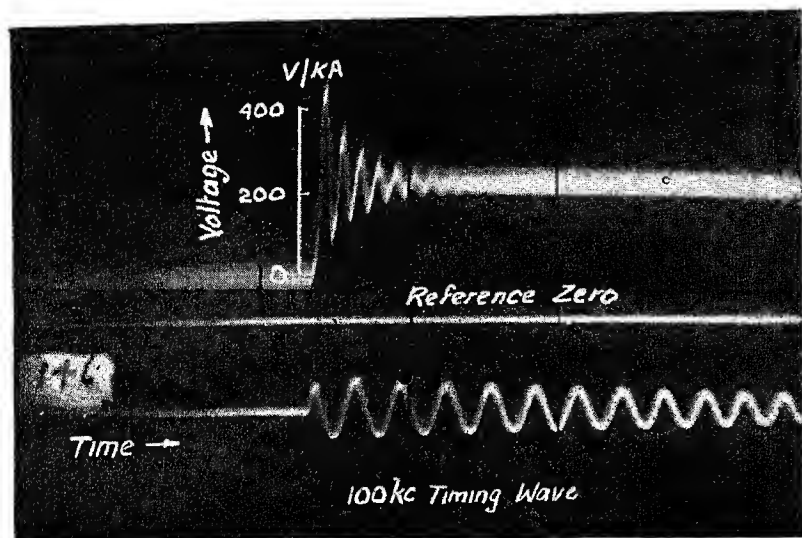


Fig. 13.—Reactor bank (Princes power station, Nechells): R.V.I. record between one phase and other two phases (earthed) of 1 500-amp. 11-kV 3.5 % reactor bank, from main-busbar side.

Referring to Fig. 12, the R.V.I. was applied between one phase and the other two phases (earthed) at C, with three phases short-circuited to earth at G.

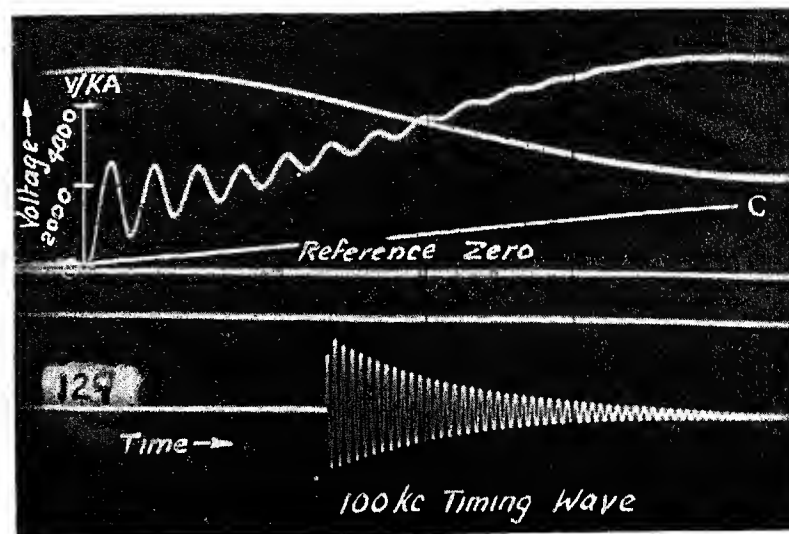


Fig. 16.—Breaker C at Sparkbrook (see Fig. 10): R.V.I. record showing transient of restriking voltage at clearance of phase-phase fault fed by transformer No. 1 with an infinite 11-kV busbar at the generating station.

The record illustrates small effect of system behind last plant unit on rate of rise, and first peak, of restriking voltage.

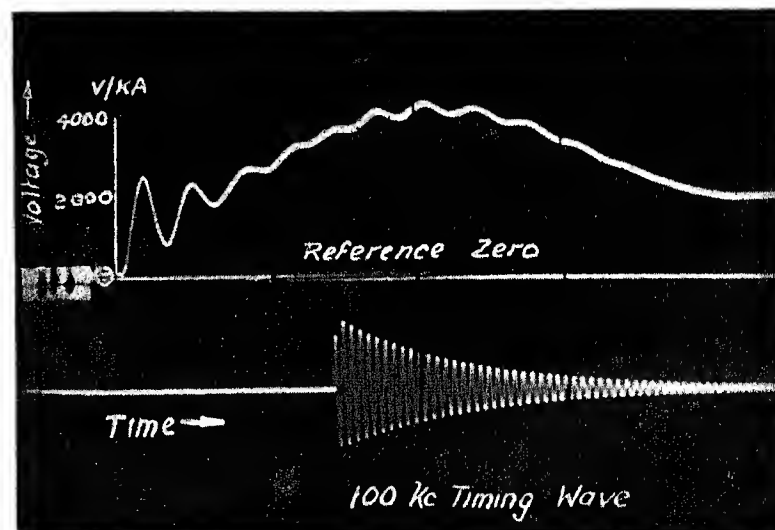
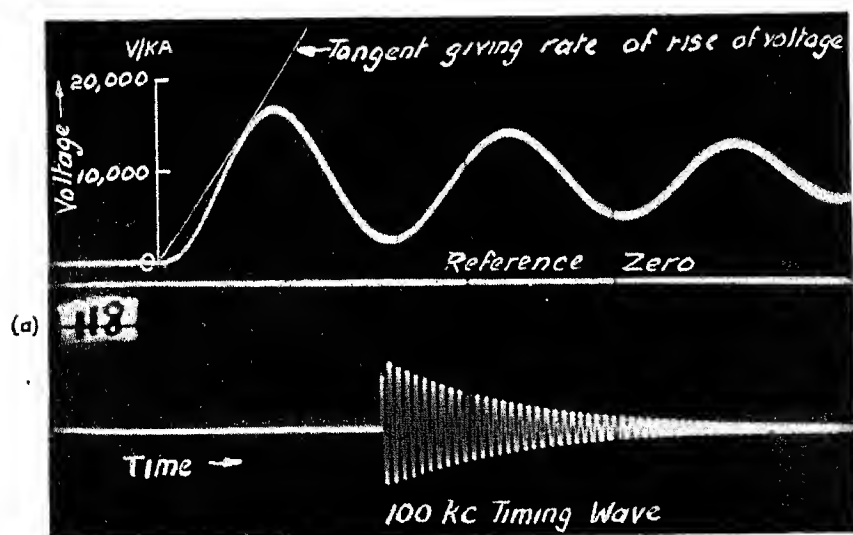


Fig. 17.—Breaker A at Bangor Road (see Fig. 9): R.V.I. record showing transient of restriking voltage at clearance of first phase of 3 phase-earth fault, with infinite 11-kV busbar at the generating station.

The record illustrates small effect of system behind last plant unit on rate of rise, and first peak, of restriking voltage.

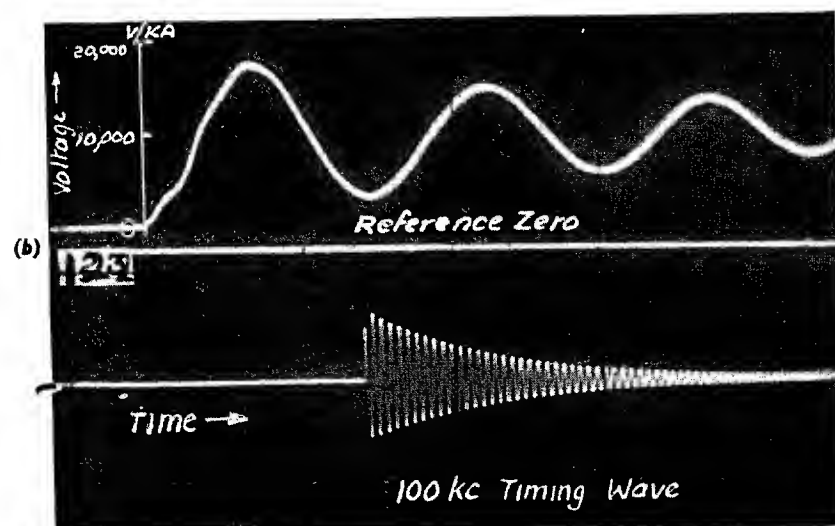


Fig. 14.—R.V.I. records obtained on neutral-earthing reactor at Bangor Road.

(a) Between three phases of neutral-earthing reactor at Bangor Road, and earth. (b) Between phase and earth of Bangor Road transformer with neutral-earthing reactor in parallel [see Fig. 2 (b)].

in Table 3, Cols. 2 and 5 respectively. Direct analysis of the R.V.I. records to obtain the reactance values per phase gives the figures shown in Cols. 3 and 4. These figures are considerably lower than the reactance per phase given in Col. 2. It has previously been suggested⁷ that the effective reactances of transformers determining the transients of restriking voltage are considerably lower than the rated reactances at power frequency, and the present results lend support to this view. This point is now being studied in some detail. Col. 5 of Table 3 shows the capacitance per phase due to the capacitance to earth of the cables between the transformer windings and the delta point at the switch, and Col. 6 shows the effective capacitance values per phase deduced from the observed frequency of the restriking-voltage transient and the reactance values given in Col. 4. The differences are attributable to the self-capaci-

above values of L and C , will in general be slightly higher than the true rates of rise by reason of the effects of the losses in the transformer, which operate mainly as parallel resistance to damp out the oscillatory portion of the restriking-voltage transient.

(b) Generators

R.V.I. measurements were made at Birmingham on an 11-kV alternator, giving 23 435 kVA at 0.8 power factor, 15.5 % reactance, connected to its circuit-breaker by a 174 yd. run of cables. The measurements were made with the rotor circuit closed and with various phase connections, and at field currents up to 75 % of full (open circuit) excitation.

Fig. 11 (Plate 1) shows four of the records obtained. These, which are entirely typical of all the records taken on the generator, are (top three) transients be-

Table 3

TRANSFORMERS: DATA ON REACTANCE AND CAPACITANCE FROM RESTRIKING-VOLTAGE-INDICATOR (R.V.I.) MEASUREMENTS AND FROM MAKER'S FIGURES

1	2	3	4	5	6	7
Transformer	Reactance values per phase from:—			Capacitance values from:—		Col. 6—Col. 5†
	Rated impedance	Sustained* amplitude on R.V.I.	Amplitude* of R.V.I. at zero time	Length × capacitance per unit length of cables from transformers to breaker†	Reactance of Col. 4 and observed frequency on R.V.I. records	
	ohm per phase at 50 c./s.			μF per phase		
Bangor Road (12 000 kVA) ..	0.72	0.63	0.63	0.0218	0.025	0.0032
Sparkbrook I (18 000 kVA) ..	0.58	§	0.46	0.0315	0.035	0.0035
Sparkbrook II (18 000 kVA) ..	0.58	§	0.47	0.038	0.039	0.001

* Values of ωL in Col. 4 are all deduced from records between phase R and the other two phases earthed; Col. 3 is the mean of two readings (0.61 and 0.65) taken between phase and two phases, and between two phases, respectively.

† Maker's figures

‡ Difference attributable to transformer self-capacitance, to departure of cable capacitance from stated value, and to errors of measurement.

§ No records available.

tance of the transformer windings, the capacitance to earth of the circuit-breaker spouts, and to departures of the cable capacitance from the rated value: the differences, whilst they vary somewhat from transformer to transformer, do not lie outside the range of values expected; for example, the self-capacitance of an 11-kV transformer winding may be of the order of 0.005 μF per phase.

From these results it may be concluded that where the combination of transformer reactance per phase, and cable capacitance to earth per phase, is such as to give rise to frequencies of the order of 20 kc./s., the effective transformer reactance determining the frequency should be taken as, say, 85 % of the rated reactance at power frequency. Where single-core cables connect the transformer secondary to the busbars, their capacitance to earth deduced from the installed length and the maker's declared capacitance per unit length per phase, will usually give a sufficiently accurate figure for the effective shunt capacitance per phase determining the oscillation frequency.

Rates of rise of voltage, calculated on the basis of the

tween phases, R-B, B-W and W-R respectively; and (bottom record) between one phase and the other two, the neutral being solidly earthed in each case. All were taken with the rotor in the same position, and with 270 amperes, supplied from a separate exciter set, flowing in the field windings.

In studying a generator with the R.V.I., it is necessary to consider whether the position of the rotor pole axis relative to the stator windings affects the results to any marked degree. The fact that the top three records of Fig. 11, which in effect give three rotor positions with respect to one phase combination, are substantially identical, shows that this point is of no great importance in the present instance, and no further reference will be made to it. It has been noticed in experiments made elsewhere that the form of R.V.I. records obtained across a generator varies considerably with the degree of excitation; in the present instance, however, records taken with zero, 30 % and 60 % of full (open circuit) excitation can hardly be distinguished from those of Fig. 11 at 75 %, so that the effect of excitation cannot be discussed here: it is quite possible, however, in the

present instance that changes in the R.V.I. record might become apparent if the field current were increased to values approaching full-load excitation. Such changes would be in the direction of increased frequency, less apparent damping, and smaller amplitude, all due to reduction of effective inductance by saturation in iron flux leakage-paths.

Even neglecting the influence of change of field current and of the position of the rotor axis, it is difficult to relate the transient of restriking voltage given by a generator to the power-frequency parameters of the machine or to give definite values to the constants of an equivalent circuit, such as that of Fig. 3, representing the machine. This arises in two ways: first, because the effective reactance or inductance and capacitance of the windings per phase varies with the type of fault interrupted; and second, because the "effective" re-

It is not convenient to have to use two values of reactance in a single calculation of rates of rise of voltage, i.e. one for amplitude and the other for frequency, and in the present state of knowledge it is probably sufficient to use a reactance value appropriate to amplitude considerations, and to apply a correction factor (less than unity) to known capacitances for the purpose of calculating frequencies. The appropriate effective capacitance values for the generator in question are given in Table 4, Col. 7: it will be seen from Col. 8 that they are of the order of 80 %–90 % of the known capacitance values.

To summarize, it may be said that in turbo-alternators of the type here considered, the effective positive and negative reactance per phase to be used in estimating transients of restriking voltage will be between 50 % and 75 % of the sub-transient reactance obtained from the rated kVA and percentage reactance of the machine,

Table 4

ALTERNATOR* WITH SOLIDLY CONNECTED CABLE (PRINCES POWER STATION, NECHELLS). DATA ON REACTANCE AND CAPACITANCE, FROM R.V.I. RECORDS

1	2	3	4	5	6	7	8
R.V.I. Record No.	Connection† in which R.V.I. was taken	Frequency of oscillatory component, kc./s.	Reactance‡ effective at frequency in Col. 3, ohm per phase at 50 c./s.	Inductance corresponding to Col. 4 (mH per phase)	Effective reactance deduced from Col. 3 and known capacitance per phase, ohm per phase at 50 c./s.	Effective capacitance from Cols. 3 and 5, μ F per phase	Col. 7 as a percentage of known equivalent shunt capacitance, %
169	Phase to phase	6	0.65	2.07	0.52	0.33	80
169	Phase to phase-phase ..	6	0.64	2.04	0.51	0.33	80
170	Phase to earth	6.3	0.52	1.65	—	0.37	90
170	Phase to phase-phase earth	6.85	0.44	1.4	—	0.37	90
170	3 phases to earth	6.9	0.27	0.86	0.24	0.36	88

* Alternator is 11 kV, 1 500 r.p.m., 23 435 kVA, 15.5 % reactance, with neutral solidly earthed, connected to switch at point of test by six single-core cables per phase, each 0.5-sq. in. cross-section and 173½ yd. long, capacitance 0.367 μ F per 1 000 yd. per core. Generator winding capacitance to earth is 0.067 μ F per phase. Total equivalent shunt capacitance is 0.41 μ F (external capacitance + 0.4 × winding capacitance). Reactance corresponding to percentage reactance = 0.8 ohm per phase.

† See Fig. 8, (a) to (e).

‡ From amplitude considerations.

actance for any phase connection may increase considerably with time within the interval considered.

The variation of "effective reactance" with time arises from the fact that the leakage flux determining this reactance passes in the main along paths through iron or copper, eddy currents in which prevent the flux from following immediately any change in the current through the windings.

These points are brought out in Table 4, which gives figures deduced from R.V.I. records across the generator referred to above. Col. 4 gives the effective reactances per phase deduced from considerations of initial amplitude: these agree amongst themselves according to the relations set out in Appendix II. Col. 6 shows the effective reactance per phase for the simple connections, deduced from consideration of observed frequencies and known (directly measured) capacitances.

The reasons why the reactance values of Col. 4 differ from those of Col. 6 and both differ from the (power frequency) sub-transient reactance of the generator, are given in Appendix IV, where the general problem of effective generator reactance is discussed.

the higher values being associated with the lower frequencies, while the effective zero phase-sequence reactance will be probably from 20 % to 40 %. Effective reactances at the interruption of faults of different types can be obtained by assembling the symmetrical reactances as shown in Appendices II and III. The effective reactance determining the frequency will in general be somewhat lower than the effective reactance determining the apparent mean of the amplitude of oscillations. Such a situation will in many cases be best met by assuming, as is done in the relevant part of the present report, that the capacitance to be used in calculation is less (in the present instance, by about 20 %) than the value obtained by direct measurement or the equivalent. The whole subject of generators in relation to transients of restriking voltage is the subject of a separate investigation which it is hoped to report in due course.

(c) Group-Feeder Reactors

Group-feeder reactors can have an important influence on the rate of rise of restriking voltage across circuit-breakers, both on the main and on the group busbar.

The highest rate of rise of voltage experienced by any breaker on the group busbars (see Fig. 12) associated with the heaviest fault kVA to which it can be subjected, arises on clearing a fault on its outgoing feeder B, on an

below its maximum when it operates to clear a fault at D. It is accordingly necessary to consider the characteristics of the group-feeder reactor from the point of view of switches A and C.

The group-feeder reactor examined at Princes power station was of 3.5 % reactance at 1 500 amperes, 11 kV. It was an air-cored unit of the cast-in-concrete type, connected to its circuit-breaker on the main busbar by 4 yd. of 3 in \times $\frac{1}{4}$ in. copper bar, micanite-covered, and mounted on insulators. The connection to the isolating link between the reactor and the group busbar was 7 yd. of similar conductor.

Fig. 13 (Plate 2) shows a typical R.V.I. record taken on the group reactor from the main-busbar side. The particular record shown is that of the transient between one phase and the other two phases earthed. It will be seen, by comparison with the 100-kc./s. timing wave, that the oscillatory component has a very high frequency indeed (about 240 kc./s.): this, of course, must lead to a very high rate of rise of voltage.

Table 5 shows the result of analysis of all the records obtained on this reactor, making it possible to deduce values for the effective reactance and capacitance of the reactors, whilst Table 6 shows some direct measurements of capacitance values.

Bridge measurements at 1 000 c./s. agree with the R.V.I. records in assigning a value of between 0.15 and 0.16 ohm per phase to the reactance of the reactor group. (The reactance value deduced from the rated percentage voltage-drop at the rated current is 0.149 ohm per phase.) One may conclude, therefore, that the effective

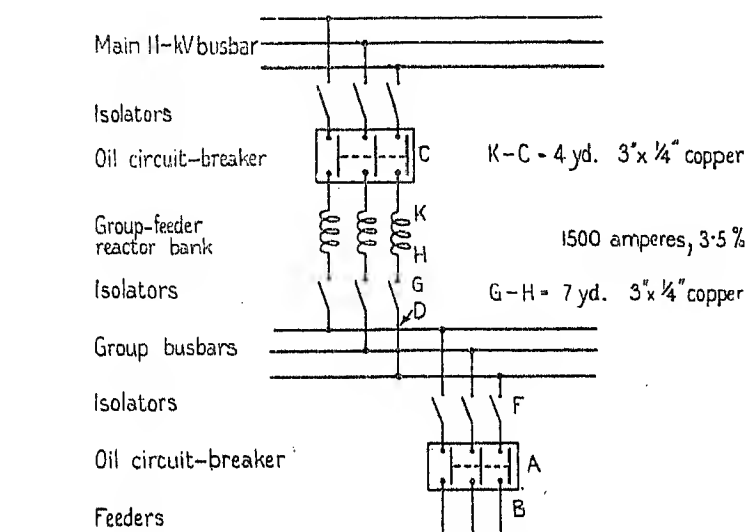


Fig. 12.—Reactor bank at Princes Power Station, Nechells: influence of group-feeder reactor on inherent rate of rise of voltage at two circuit-breaker conditions (A and C).

Breaker A has its highest rate of rise associated with the heaviest fault-kVA condition, namely that which prevails when it clears a fault at B and there are no other outgoing feeders on the group busbar. Breaker C has its highest rate of rise at a fault kVA considerably below its maximum kVA, when it clears a fault at D.

occasion when there are no other outgoing feeders on that particular group busbar at the moment of clearing. The group-feeder breaker C, also, will experience a very high rate of rise of voltage at a fault kVA considerably

Table 5

GROUP-FEEDER REACTOR BANK AT PRINCES POWER STATION, NECHELLS (SEE FIG. 12). DATA ON REACTANCE AND CAPACITANCE, FROM R.V.I. RECORDS

1	2	3	4	5	6
R.V.I. No.	Connection in which R.V.I. was taken	Frequency of oscillatory component (kc./s.)	Reactance from R.V.I. measurements, (Ω /phase at 50 c./s.)	Inductance corresponding to Col. 4 (mH)	Capacitance per phase to give frequency of Col. 3 with inductance of Col. 5 ($\mu\mu\text{F}$)

From group-feeder switch on main busbar (C, Fig. 12)

141	Phase to earth	226	0.16	0.51	890
142	Phase to phase	234	0.16	0.51	825
143	Phase to phase-earth	240	0.16	0.51	748
144	Phase to phase-phase	236	0.16	0.51	800
145	Phase to phase-phase	240	0.15	0.48	840
146	Phase to phase-phase earth	238	0.15	0.48	835
147	Three phases to earth	268	0.16	0.51	576
148	Phase to phase-earth*	164	0.15	0.48	1 880*

From outgoing feeder-switch isolators on group busbars

155	Phase to phase	190	0.16	0.51	1 235
156	Phase to earth	190	0.17	0.54	1 200

* With 1 000 $\mu\mu\text{F}$ added between live phase and earth, to provide check at lower frequency.

reactance of an air-cored current-limiting reactor under transient conditions agrees reasonably well with the value given by the rated percentage voltage-drop at rated current: this holds at frequencies up to 240 kc./s. so far examined.

On account of the difficulty of physically separating parts of the system, it was not possible to make bridge

Table 6

GROUP BUSBARS, PRINCES POWER STATION, NECHELLS:
BRIDGE MEASUREMENTS OF CAPACITANCE

1	2	3
Capacitance in	Isolator F to Isolator G* (all other isolators on group busbar open)	Isolator F to oil circuit-breaker C*
	μF per phase	μF per phase
(a) Phase to phase† ..	690	140
(b) Phase to earth† ..	1 410	2 290
(c) 3 phases to earth ..	3 890	6 700
From (c) per phase to earth	1 300	2 230
From (a), (b), (c), direct interphase	60‡	50‡

* References are to Fig. 12.

† Other phase or phases floating.

‡ These values are too small, in comparison with the magnitudes from which they were determined, for the measurements to be accurate.

measurements of the actual capacitances deduced from R.V.I. measurements, but the latter figures appear quite compatible with the results of bridge measurements set out in Table 6.

The self-capacitance of air-cored reactors is quite low—much lower than that of transformers of similar impedance—and so it is in situations such as that here discussed, where an air-cored-reactor group is connected to a circuit-breaker by very short lengths of very low-capacitance lead, that the highest rates of rise of voltage met with in practice will be encountered.

(d) Neutral-Earthing Reactors

A neutral-earthing reactor never alone determines a transient of restriking voltage in any practical fault condition. It does, however, play an important part in the determination of the transient at the clearing of a phase-earth short-circuit.

It has been shown by Evans and Monteith¹⁴ that the transient of restriking voltage at the clearance of a phase-earth fault is obtained by taking separately the transient on the interruption of one-third of the total fault current regarded as flowing through the positive, negative and zero phase-sequence systems respectively. The transient at the interruption of the phase-earth fault is then that transient of which the ordinate at any given time is the sum of the corresponding ordinates of the three separate transients.

The neutral-earthing reactor at Bangor Road had a reactance of 7.07 ohms to earth-fault current (i.e. the zero phase-sequence impedance per phase was 21.2

ohms). The zero phase-sequence capacitance of the system per phase was, say, $0.026 \mu\text{F}$ [$0.022 \mu\text{F}$ for the cables, see Table 3, plus (say) $0.004 \mu\text{F}$ for transformer winding capacitance]. These figures give a resonant frequency of 3.9 kc./s., which agrees well with the observed figures. An R.V.I. record relating to the zero phase-sequence system alone appears in Fig. 14(a), Plate 2. The corresponding record relating to the interruption of a phase-earth fault is shown in Fig. 14(b). It will be clear that ordinates to the curve of Fig. 14(b) are equal to those of Fig. 14(a) together with two-thirds of the corresponding ordinates to the curve of Fig. 2(a) (which represents an R.V.I. record for the corresponding positive or negative phase-sequence system). In such a case the rate of rise of voltage at the clearance of the phase-earth fault is almost entirely governed by the zero phase-sequence system, the effect of the negative and positive phase-sequence systems accounting together for only about 7% of the rate of rise indicated by Fig. 14(b).

(6) INFLUENCE OF THE SUPPLY SYSTEM ON THE TRANSIENT OF RESTRIKING VOLTAGE

The discussion recorded above has mainly related to that component of the transient of restriking voltage which is due to the plant nearest the fault, e.g. transformers in substations, group-feeder reactors in generating stations, etc. The supply system behind this plant also has a component in the restriking-voltage transient, but its effect on the rate of rise of voltage and the first peak of restriking voltage is frequently negligible.

Consider, for instance, a substation fed by a single transformer. The complete system determining the transient of restriking voltage at the clearance of, say, a

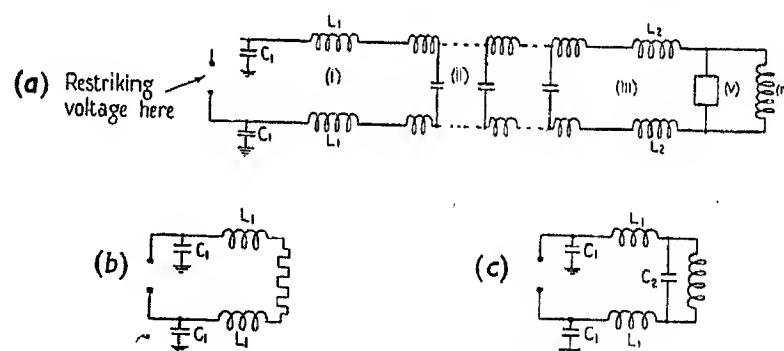


Fig. 15.—Simplification of system behind last plant unit: method adopted in calculating rates of rise, and first peaks, of restriking voltage.

(a) (i) Transformer at substation. (ii) Cable inductance and capacitance referred to substation busbar voltage. (iii) Transformer at generating station. (iv) Reactance of generating plant on station busbars. (v) Impedance representing capacitance of station busbars plus effective impedance of all outgoing feeders. (b) Cable (ii) and system beyond it represented by resistance equivalent to surge impedance of cable. (c) Cable (ii) and system beyond it represented by single oscillatory system, where $L_1 = 2L$ and $C_2 =$ total feeder capacitance referred to busbar voltage.

phase-phase fault, is shown in Fig. 15(a). If the cable (ii) there shown is fairly long then, owing to the finite velocity of wave propagation along the cable, some time must elapse before the effects of conditions at the far end of the cable appear on phenomena applied at the near end. Therefore, over a certain period of time the transient of restriking voltage may be calculated as though the cable, and the part of the system on the

supply side of it, were replaced by a resistance equal to the effective surge impedance of the cable, at the high-voltage terminal of the substation transformer, as in Fig. 15(b).

In a particular instance (Sparkbrook transformer No. 1) the capacitance to earth per phase of the cable between transformer secondary and substation busbars was $0.032 \mu\text{F}$. The reactance per phase of the substation transformer was 0.46 ohm . The 33-kV cable was of the S.L. type, 15 216 yd. long, and of resistance $0.0974 \text{ ohm per mile}$, star reactance $0.104 \text{ ohm per mile}$, and star capacitance $0.28 \mu\text{F per mile}$. The nominal (phase-phase) surge impedance was thus $\sqrt{L/C} = 75 \text{ ohms}$, and the nominal propagation time $9.6 \text{ microsec. per } 1000 \text{ yd.}$ No data directly relating to the effective surge impedance and propagation time of S.L. cable are available, but from figures given in a previous E.R.A. report⁶ dealing with three single-core cables laid in trefoil it is fairly safe to assume that in both cases the effective value will be about 80 % of the nominal value, giving a phase-phase surge impedance of 60 ohms, and a propagation time of $7.7 \text{ microsec. per } 1000 \text{ yd.}$ The transformer ratio is 3:1 (including the star/delta transformation), so that the effective surge impedance of the cable referred to busbar voltage is about 6.7 ohms. The total propagation time along the cable and back is about 230 microsec.; thus over the first 230 microsec. or so the transient of restriking voltage is that arising from a network like that of Fig. 15(b), with the values there given. Provided, as must happen with the vast majority of cases, that R' is small compared with L/C , the transient of restriking voltage per kilo-ampere is substantially that for Fig. 15(b) with $R = 0$, together with a term $0.445Rt \times 10^6 \text{ volts}$ ($0.445 \times 10^6 = 1414 \times 314$). The transient with $R = 0$ is that discussed in the previous Section (i.e. the transient due to the transformer regarded as short-circuited at its high-voltage terminals). Fig. 16 (Plate 2) shows the transient arising on such a system as that of Fig. 15 (b). The line OC represents that component of the voltage transient which is due to the surge impedance of cables on the high-voltage side of the transformer. The effect of this component on the front of the transient is negligible: the overall rate of rise of voltage is 115 volts per microsec. whilst that due to the presence of the cables is only about 3 volts per microsec. Here, then, the impedance due to the transformers alone quite adequately represents the total rate of rise of restriking voltage at the substation.

Similar arguments apply when the cable is not sufficiently long for its propagation time to be of any importance (i.e. when the voltage drop along it under power-frequency conditions is quite negligible compared with that in the transformer at either end). Here the conditions shown in Fig. 15(b) can no longer be said to hold, and instead the system can be represented by Fig. 15(c), where L and C are as before but C_1 is the capacitance of the 33-kV cables referred to 11 kV, and L_1 is the inductance of the transformer at the generating station. Here the transient of restriking voltage is of the form

$$e = K[L(1 - \cos \omega t) + L_1(1 - \cos \omega_1 t)]$$

where $\omega^2 = LC$ and $\omega_1^2 = L_1(C + C_1)$. L_1 will usually

equal L , and $\omega_1^2/\omega^2 = C/(C + C_1)$. C_1 will usually be very large compared with C , and so ω will be very much greater than ω_1 . Whilst the term in ω is attaining its peak value (i.e. over the time $\omega t = \pi$) the term in ω_1 will only have attained a value

$$L_1 \left(1 - \cos \frac{\pi \omega_1}{\omega} \right)$$

Writing $\omega = 10\omega_1$ (probably a minimum value for the type of system we are considering), we find that the value of the term in ω_1 when that in ω is at its peak is

$$L_1 \left(1 - \cos \frac{\pi}{10} \right) = 0.05L_1$$

Thus the term in ω_1 cannot increase the rate of rise of restriking voltage by more than about 1.5 %: this percentage will decrease with ω_1/ω , i.e. as the physical length of the cables between the transformers increases. An example of a transient of this type appears in Fig. 17 (Plate 2). The higher-frequency component of the transient is that due to the substation transformer: the lower-frequency component is that due to the transformer at the generating station end, oscillating with the capacitance of the feeders. The rate of rise of voltage is substantially unaffected by the lower-frequency component.

The same arguments as are used above can be applied to show that the effect of impedance units numbered (iv) and (v) in Fig. 15(a) are quite negligible so far as the rate of rise of voltage, and first peak of restriking voltage, are concerned: they do, however, enter in some degree into the determination of the ultimate peak restriking voltage, with which the present investigation does not purport to deal.

In general, it may be said that when the transient of restriking voltage has oscillatory components of two or more frequencies, and the highest frequency is more than 5 times the next frequency, and is of more or less equal amplitude, it is fairly safe to estimate rates of rise of voltage as if the plant giving rise to the highest-frequency term only were present; since the error due to neglecting lower-frequency terms will probably be more than outweighed by errors due to neglecting damping.

(7) TRANSIENTS OF RESTRIKING VOLTAGE AT POINTS INVESTIGATED

(a) Transformer-Fed Substations

(i) Rates of rise per kilo-ampere fault current.

It has been shown above that in many cases it is possible to estimate the rate of rise of restriking voltage, and the first peak of restriking voltage, with sufficient accuracy by considering only the transient across the last plant unit in the supply network; and a Table (Table 1) has been presented by means of which can be obtained the rate of rise and first peak of restriking voltage per kilo-ampere fault current, under different fault conditions, neglecting losses in the oscillatory system. Comparison may now be made between the rates of rise, etc., obtained by the use of such a Table with reference to transformer-fed substations, and the values obtained by the use of the R.V.I., which of course takes account of the losses.

Table 7 shows figures resulting from the application of Table 1 to a single transformer substation, and the comparable figures obtained from R.V.I. records. Here Cols. 1, 2, and 3 correspond to Cols. 1, 2, and 3 of Table 1. Cols. 4 and 5 show the rates of rise of voltage and first peak of restriking voltage per kilo-ampere, calculated from system constants and neglecting losses but with the inductance value adjusted as shown necessary in Section (5). Col. 6 refers to the appropriate R.V.I. record, and Cols. 7 and 8 show the rates of rise of voltage and peak restriking voltage per kilo-ampere measured from R.V.I.

temporary leads (of negligible capacitance compared with that of the cable between A and the transformers). The figures thus relate to conditions which would exist for breakers on the substation 11-kV bars if the latter were connected to Switch A by negligibly short lengths of cable. There was, in fact, quite a considerable length between A and the busbar, so that the rates of rise of voltage on the busbar will be somewhat lower than Table 7 indicates.

The figures given in the lower part of Table 7 are directly applicable to Switch A (Fig. 9).

Table 7

12 000-kVA 33/11-kV TRANSFORMER AT BANGOR ROAD (FIG. 9)*: COMPARISON OF R.V.I. MEASUREMENTS OF RATES OF RISE, AND FIRST PEAK, OF RESTRIKING VOLTAGE PER KILO-AMPERE FAULT CURRENT, WITH VALUES DEDUCED FROM APPROPRIATE SYSTEM PARAMETERS AND TABLE 1, COLS. 11-14

1 and 2	3	4	5	6	7	8	9	
Item and type of fault†	Stage in clearance‡	From Table 1 and system parameters‡		R.V.I. record No.	From R.V.I. measurements		Per pole (1) or per 2 poles (2)	
		Rate of rise (V/microsec./kA)	1st peak (V/kA)		Rate of rise (V/microsec./kA)	1st peak (V/kA)		
(a) Neutral earth on supply side								
(i) 3-phase-earth	Phase to phase-phase-earth	109	2 680	119	105	1 960	(1)	
(ii) 2-phase-earth	Phase to phase-earth	113	3 030	121	108	2 600	(1)	
(iii) Phase-earth	Phase to earth	176	21 800	122	160	17 700	(1)	
(iv) 3-phase	Phase to phase-phase	134	2 680	120	127	1 960	(2)	
(v) Phase-phase	Phase to phase	176	3 560	122	152	3 180	(2)	
(b) Neutral earth on side remote from supply								
(vi) 3-phase-earth	Phase to phase-phase-earth	109	2 680	111	110	2 440	(1)	
(vii) 2-phase-earth	Unearthed phase	}	Largely determined by load conditions				(1)	
(viii) Phase-earth	One unearthed phase						(1)	
(ix) 3-phase	Phase to phase-phase		134	2 680	§	130	2 500	(1)
(x) Phase-phase	Phase to phase		268	3 570	§	173	3 340	(2)

* For inherent rates of rise of voltage at Bangor Road, see Table 10.

† This neglects losses, but inductance values are adjusted (see Table 3).

‡ No R.V.I. records obtained in these connections: values in Cols. 7 and 8 deduced from other appropriate records. Cols. 4 and 5 obtained by use of Table 1; Cols. 7 and 8 obtained from R.V.I. records.

† See Fig. 8.

records. Col. 9 states whether the restriking voltage in question appears across one or two poles of the circuit-breaker.

It will be seen that in general the agreement between Cols. 4 and 7 and 5 and 8 is quite good, bearing in mind that the values given in the "R.V.I." columns should be lower than in those showing calculated figures by reason of the neglect of the losses in the latter. The excessively low values in Col. 8 for the 3-phase and 3-phase-earth cases as compared with Col. 5 are probably due to the "beating" referred to in Section 5(a), the source of which has not yet been properly investigated.

The upper set of figures in Table 7 actually refer to Switch A of Fig. 9, with the neutral-earthing reactor connected to the transformer side of the switch by short

For a substation fed by two or more transformers in parallel (e.g. Sparkbrook, Fig. 10, which has two in parallel), conditions are slightly different. Here, the switches C, D, between the transformers and the busbars are the only ones which can be called upon to clear with the earth connection on the fault side of the circuit-breaker. These switches can only be called upon to handle, in this connection, the fault current supplied by either one transformer (when the breaker is clearing the transformers from a busbar fault) or (assuming a station similar to that represented in Fig. 10 but with more than two similar feeders) all the other transformers in the station (when the breaker is clearing the busbars from a fault on the cable between switch and transformer). In the latter event the chances that the switch in question

Table 8

ONE 18 000-KVA 33/11-KV TRANSFORMER AT SPARKBROOK* (FIG. 10, No. 1): COMPARISON OF R.V.I. MEASUREMENTS OF RATES OF RISE, AND FIRST PEAK, OF RESTRIKING VOLTAGE PER KILO-AMPERE FAULT CURRENT, WITH VALUES DEDUCED FROM APPROPRIATE SYSTEM PARAMETERS AND TABLE 1, COLS. 11-14

1 and 2	3	4	5	6	7	8	9
Item and type of fault†	Stage in clearance‡	From Table 1 and system parameters‡		R.V.I. record No.	From R.V.I. measurements		Per pole (1) or per 2 poles (2)
		Rate of rise (V/microsec./kA)	1st peak (V/kA)		Rate of rise (V/microsec./kA)	1st peak V/kA	
(a) Neutral earth on supply side							
(i) 3-phase-earth	Phase to phase-phase-earth	70	1 950	132	66	1 790	(1)
(ii) 2-phase-earth	Phase to phase-earth	72	2 200	130	77	2 000	(1)
(iii) Phase-earth	Phase to earth	75	7 540	128	66	4 900	(1)
(iv) 3-phase	Phase to phase-phase	85	1 950	131	87	1 900	(1)
(v) Phase-phase	Phase to phase	114	2 600	129	115	2 480	(2)
(b) Neutral earth on side remote from supply							
(vi) 3-phase-earth	Phase to phase-phase-earth	84	1 950	125	91	1 850	(1)
(vii) 2-phase-earth	Unearthed phase	}	Largely determined by load conditions				(1)
(viii) Phase-earth	One unearthed phase		(1)				
(ix) 3-phase	Phase to phase-phase	84	1 950	§	—	—	(1)
(x) Phase-phase	Phase to phase	114	2 600	§	—	—	(2)

* For inherent rates of rise of voltage at Sparkbrook, see Tables 11 and 12.
† This neglects loss, but inductance values are adjusted as in Table 3.

† See Fig. 8.
§ No R.V.I. records obtained in these connections.

Table 9

TWO 18 000-KVA 33/11-KV TRANSFORMERS (SPARKBROOK NOS. 1 AND 2)* IN PARALLEL ON ONE BUSBAR (SEE FIG. 10): COMPARISON OF R.V.I. MEASUREMENTS OF RATES OF RISE, AND FIRST PEAK, OF RESTRIKING VOLTAGE PER KILO-AMPERE FAULT CURRENT, WITH VALUES DEDUCED FROM APPROPRIATE SYSTEM PARAMETERS AND TABLE 1, COLS. 11-14

1 and 2	3	4	5	6	7	8	9
Item and type of fault†	Stage in clearance‡	From Table 1 and system parameters‡		R.V.I. record No.	From R.V.I. measurements		Per pole (1) or per 2 poles (2)
		Rate of rise (V/microsec./kA)	1st peak (V/kA)		Rate of rise (V/microsec./kA)	1st peak (V/kA)	
<i>Neutral earth on supply side</i>							
(i) 3-phase-earth	Phase to phase-phase earth	38	970	139	36	870	(1)
(ii) 2-phase-earth	Phase to phase-earth	39	1 100	137	36	900	(1)
(iii) Phase-earth	Phase to earth	119	6 900	135	90	4 900	(1)
(iv) 3-phase	Phase to phase-phase	47	970	138	45	870	(1)
(v) Phase-phase	Phase to phase	63	1 300	136	60	1 140	(2)

The condition of a neutral earth on the side remote from the fault cannot arise.

* For inherent rates of rise at Sparkbrook, see Tables 11 and 13.

† See Fig. 8.

‡ This neglects loss, but inductance values are adjusted as in Table 3.

will be called upon to clear *after* the feed into the fault from its transformer side has been cleared by the generating-station breaker are very remote, as the generating-station breakers are usually set with longer time-lag. Unless this happened the breaker would be operating under reduced effective recovery operating voltage; so that we need not consider in this connection the condition analogous to that dealt with in the lower part of Table 7.

Table 8(a) shows the rates of rise of voltage per kilo-ampere which exist for any of the outgoing feeder switches on the 11-kV busbar clearing a fault just at the feeder side of the switch, when the supply to the busbar was maintained by Feeder A and Transformer No. 1 only (see Fig. 10). These rates of rise will only appear when there are no other outgoing feeders on the busbar.

these figures by the appropriate fault current in kilo-amperes to obtain the inherent rates of rise under fault conditions. These figures are given, for the Bangor Road substation, in Table 10, the fault currents being calculated for the supply condition giving the heaviest fault kVA at the substation. In this Table the figures under (b) apply to Switch A, Fig. 9, opening on a busbar fault. Any other breaker on the substation busbars, opening a fault on its outgoing feeder, will have to deal with rates of rise of voltage rather lower than those given under (a).

Similar figures for the Sparkbrook substation, supplied through one transformer only, appear in Table 11. Here the figures under (a) apply for any breaker to an outgoing feeder from the substation busbars, opening a fault on its outgoing feeder, when No. 1 transformer only

Table 10

SUBSTATION AT BANGOR ROAD (FIG. 9): INHERENT RATES OF RISE, AND FIRST PEAKS, OF RESTRIKING VOLTAGE

1 and 2	3	4	5	6	7
Item and type of fault*	Stage in clearance*	Fault current cleared (kA)	Rate of rise of restriking voltage (volts/microsec.)†	First peak of restriking voltage (V)†	Per pole (1) or per two poles (2)
(a) Earth on supply side					
(i) 3-phase-earth	Phase to phase-phase-earth	3·840	403	7 520‡	(1)
(ii) 2-phase-earth	Phase to phase-earth	3·24§	350	8 650	(1)
(iii) Phase-earth	Phase to earth	0·66	105	11 600	(1)
(iv) 3-phase	Phase to phase-phase	3·840	488	7 520‡	(1)
(v) Phase-phase	Phase to phase	3·320	505	10 650	(2)
(b) Earth on side remote from supply					
(vi) 3-phase-earth	Phase to phase-phase-earth	3·84	423	9 360	(1)
(vii) 2-phase-earth	Unearthed phase	} Depends on load conditions	}	}	(1)
(viii) Phase-earth	One unearthed phase				(1)
(ix) 3-phase	Phase to phase-phase				(1)
(x) Phase-phase	Phase to phase	3·32	575	11 100	(2)

* See Fig. 8.

† These values are probably rather low, because of the "beating" mentioned in Section (3): the cause of this has not yet been explained.

‡ Smaller of two currents.

§ From R.V.I. records and calculated fault currents.

Table 8(b) shows the rate of rise across the first phase to clear of a 3-phase-earth fault when Breaker C operates to clear a busbar fault in the same conditions. These again are unaffected by the condition of any other switch-gear in the substation.

The switchgear on the 11-kV substation busbars can be called upon to clear faults fed by two feeders and transformers in parallel, but only with the neutral earth connection on the supply side of the switch. The relevant figures for rate of rise of voltage per kilo-ampere and peak restriking voltage appear in Table 9.

(ii) Inherent rates of rise of voltage.

Figures having been obtained for the rates of rise of voltage, and first peak of restriking voltage, per kilo-ampere fault current, it is only necessary to multiply

is supplying the busbar. If No. 2 transformer only was supplying the fault the rates of rise would be very slightly lower. The values under (b) apply for Breaker C (Fig. 10) opening on a busbar fault, when Breaker D is already open. Rates of rise of voltage are in general rather higher under the latter circumstances than under the former, by reason of the fact that in the one case the busbar capacitance is effectively in parallel with the transformers, whilst in the other it is short-circuited. Here again, rates of rise with No. 2 transformer supplying the busbars will be very slightly lower.

Corresponding figures for any breaker to an outgoing feeder from the substation busbars, when the supply to the busbars is maintained through two transformers, appear in Table 12. The rates of rise of voltage are here intermediate between those in the two sets in Tables 10 and 11, for obvious reasons.

(b) Generating-Station Main Busbars

(i) Rates of rise per kilo-ampere fault current.

Any one breaker on the main busbars (see Nechells, Fig. 1) operates at its maximum kVA when clearing a

obtained by the use of Table 1 and by R.V.I. records, for a single generator with its neutral point solidly earthed. It is only in very unusual circumstances that breakers on the main busbars could be called upon to clear a fault with the neutral earth on the fault side of

Table 11

SUBSTATION AT SPARKBROOK (FIG. 10): INHERENT RATES OF RISE, AND FIRST PEAKS, OF RESTRIKING VOLTAGE (BREAKER BETWEEN NO. 1 TRANSFORMER AND BUSBARS CLEARING FAULT ON BUSBARS)

1 and 2	3	4	5	6	7
Item and type of fault*	Stage in clearance*	Fault current cleared (kA)	Rate of rise of restriking voltage (volts per microsec.)†	First peak of restriking voltage (V)†	Per pole (1) or per two poles (2)
<i>(a) Neutral earth on supply side</i>					
(i) 3-phase-earth	Phase to phase-phase-earth	4.4	290	7 890	(1)
(ii) 2-phase-earth	Phase to phase-earth	3.45‡	268	6 900	(1)
(iii) Phase-earth	Phase to earth	1.15	76	5 650	(1)
(iv) 3-phase	Phase to phase-phase	4.4	382	8 390	(1)
(v) Phase-phase	Phase to phase	3.81	439	9 450	(2)
<i>(b) Neutral earth on side remote from supply</i>					
(vi) 3 phase-earth	Phase to phase-phase-earth	4.4	400	8 150	(1)
(vii) 2 phase-earth	Unearthed phase	} Largely depends on load conditions			(1)
(viii) Phase-earth	One unearthed phase				(1)
(ix) 3 phase	Phase to phase-phase	4.4	462	8 400	(1)
(x) Phase-phase	Phase to phase	3.81	536	9 500	(2)

* See Fig. 8.

† From R.V.I. records and calculated fault currents.

‡ Smaller of two currents.

fault near the circuit-breaker on its outgoing feeder supplied by all the generators in parallel. It is thus the generators, with their cables up to the busbars, the switch, and so it is not necessary to refer to this condition.

In Table 13, the reactance (ωL) values in Col. 4 are

Table 12

SUBSTATION AT SPARKBROOK (FIG. 10): INHERENT RATES OF RISE, AND FIRST PEAKS, OF RESTRIKING VOLTAGE (BREAKER ON OUTGOING FEEDER CLEARING FAULT ON FEEDER, SUPPLY TO BUSBARS THROUGH NOS. 1 AND 2 TRANSFORMERS)

1 and 2	3	4	5	6	7
Item and type of fault*	Stage in clearance*	Fault current cleared (kA)	Rate of rise of restriking voltage (volts per microsec.)†	First peak of restriking voltage (V)†	Per pole (1) or per two poles (2)

Neutral earth on supply side

(i) 3-phase-earth	Phase to phase-phase-earth	8.53	309	7 420	(1)
(ii) 2-phase-earth	Phase to phase-earth	7.34‡	263	6 600	(1)
(iii) Phase-earth	Phase to earth	1.27	114	6 220	(1)
(iv) 3-phase	Phase to phase-phase	8.53	374	7 420	(1)
(v) Phase-phase	Phase to phase	7.37	444	10 200	(2)

The condition of a neutral earth on the side nearer to the fault cannot arise

* See Fig. 8.

† From R.V.I. records and calculated fault currents.

‡ Smaller of two currents.

which determine the highest rate of rise of voltage encountered by these breakers working at their maximum kVA.

Table 13 shows the relation between rates of rise, etc.,

deduced as described in Section 5(b) above, from the R.V.I. records by the method of symmetrical components. The frequency figures in Col. 5 are those given by the reactance value of Col. 4 taken with the capaci-

tance deduced from the R.V.I. records in the phase-to-phase and phase to phase-phase cases: it is probable that this is not completely justified, as there are one or two

The above figures show very low rates of rise of voltage. Certain circuit-breakers on the main busbars, however, must handle very high rates of rise of voltage under

Table 13

11-kV ALTERNATOR, 23 425 kVA, 15·5 % REACTANCE, 1 500 R.P.M., WITH 173²/₃-YD. RUN OF CABLE (PRINCES POWER STATION)*: COMPARISON OF R.V.I. MEASUREMENTS OF RATES OF RISE, AND FIRST PEAKS, OF RESTRIKING VOLTAGE PER KILO-AMPERE FAULT CURRENT, WITH VALUES DEDUCED FROM APPROPRIATE SYSTEM PARAMETERS AND TABLE 1, COLS. 11-14

1 and 2	3	4	5	6	7	8	9	10
Item and type of fault†	Stage in clearance‡	Effective ωL value (ohms)‡	f (kc./s.)	From Table 1 and system parameters§		R.V.I. record No.	From R.V.I. records	
				Rate of rise of voltage (V/microsec./kA)	Peak of restriking voltage (V/kA)		Rate of rise of voltage (V/microsec./kA)	Peak voltage (V/kA)
<i>Neutral earth on supply side</i>								
(i) 3-phase-earth	Phase to phase-phase-earth	0·44	7·3	20·6	1 240	170	15·4	1 130
(ii) 2-phase-earth	Phase to phase-earth	0·49	6·9	21·7	1 390	No record taken		
(iii) Phase-earth	Phase to earth	0·52	6·7	22·0	1 470	170	17·1	1 200
(iv) 3-phase	Phase to phase-phase	0·97	6·0	33·5	2 750	169	28·6	2 450
(v) 3-phase	Phase to phase	1·30	6·0	45·0	3 680	169	32·7	3 240

* For inherent rates of rise on busbars fed by alternators, see Table 15

† See Fig. 8.

‡ See Table 4.

§ These figures neglect losses, but inductance and capacitance values are adjusted (see Table 4).

points in connection with the capacitances of the generators which have still to be cleared up; but the error due to this cause will probably be quite small. Here again

certain fault conditions. A breaker, for instance, to a group busbar, opening on a fault on this busbar (see Fig. 12), meets a very high-frequency component of

Table 14

GROUP-FEEDER REACTOR FROM MAIN-BUSBAR SIDE AT PRINCES POWER STATION, NECHELLS (SEE FIG. 12)*: COMPARISON OF R.V.I. MEASUREMENTS OF RATES OF RISE, AND FIRST PEAKS, OF RESTRIKING VOLTAGE PER KILO-AMPERE FAULT CURRENT, WITH VALUES DEDUCED FROM APPROPRIATE SYSTEM PARAMETERS AND TABLE 1, COLS. 11-14

1 and 2	3	4	5	6	7	8	9
Item and type of fault†	Stage in clearance‡	From Table 1 and system parameters		R.V.I. record No.	From R.V.I. measurements		Per pole (1) or per 2 poles (2)
		Rate of rise (V/microsec./kA)	First peak (V/kA)		Rate of rise (V/microsec./kA)	First peak (V/kA)	

Earth on supply side (neutral earth resistor), reactors on fault side, of switch

(i) 3-phase-earth	Phase to phase-phase-earth	232	425	146	196	420	(1)
(ii) 2-phase-earth	Phase to phase-earth	232	425	143	193	†	(1)
(iii) Phase-earth	Phase to earth	232	425	141	188	†	(1)
(iv) 3-phase	Phase to phase-phase	348§	638§	144§	321§	611§	(1)
(v) Phase-phase	Phase to phase	464	850	142	358	†	(2)

* Condition represented is that of Circuit-breaker C clearing fault beyond H.

† Record unreliable: R.V.I. reads peaks low on range used for these records at frequencies above 150 kc./s.

‡ In practice these figures will probably come down towards those in Row 1.

§ See Fig. 8.

the R.V.I. records are in reasonably good agreement with the calculated figures, bearing in mind that the latter neglect losses and consequent damping.

restriking voltage, arising from the decay of voltage across the reactor. Table 14 shows for this case figures of rate of rise of voltage and first-peak restriking voltage

obtained by the use of Table 1 and by the R.V.I. respectively, as before: here again the agreement is reasonable. These rates of rise of voltage are considerably higher than those met with at the heavier fault kVA.

(ii) **Inherent rates of rise of voltage.**

It was obviously not possible to take R.V.I. records* in the conditions when there was enough plant on the

on the busbars approximately equal to that existing in practice under full-load conditions (925 000 kVA), of which, however, part is supplied from alternators and part from the transformers from two grid feeders. The latter would probably give lower rates of rise of voltage per kilo-ampere than the alternators, so that the calculated figures are probably slightly higher than exist in practice.

Table 15

MAIN BUSBARS (PRINCES POWER STATION, NECHELLS)*: INHERENT RATES OF RISE, AND FIRST PEAKS, OF RESTRIKING VOLTAGE (BUSBARS ASSUMED FED BY 8 ALTERNATORS SIMILAR TO THAT TREATED IN TABLE 13)

1 and 2	3	4	5	6	7
Item and type of fault†	Stage in clearance†	Fault current cleared (kA)	Rate of rise of restriking voltage (V/microsec.)‡	First peak of restriking voltage (V)‡	Per pole (1) or per two poles (2)
(i) 3-phase-earth	Phase to phase-phase earth	62·8	229	18 700	(1)
(ii) 2-phase-earth	Phase to phase-earth	54	284§	25 400§	(1)
(iii) Phase-earth	Phase to earth	0·95	10-12	1 000-1 200	(1)
(iv) 3-phase	Phase to phase-phase	62·8	263	19 300	(1)
(v) Phase-phase	Phase to phase	54·5	307	27 250	(2)

* See Fig. 12. Switch C clearing fault on connection to reactor.

† From measurements on R.V.I. records, adjusted for currents [except Row (ii)].

‡ From R.V.I. record taken on dummy circuit as in Fig. 22(iv). Dummy circuit was undamped, and these figures are probably at least 10 % too high.

† See Fig. 8.

busbars to give the maximum kVA to which the breakers were subject, so that to give figures for rates of rise of voltage under these conditions, from data available for one generator only, it is necessary to make some assumptions. If it be assumed that under peak-load conditions

The calculated figures referred to above are given in Table 15. Here, the figures for the unearthed faults [Rows (iv) and (v)] are obtained by direct extension from Table 13 (since eight similar alternators in parallel give the same inherent rate of rise of voltage per kilo-

Table 16

BREAKER ON MAIN BUSBAR (PRINCES POWER STATION, NECHELLS) CLEARING FAULT ON GROUP BUSBAR*: INHERENT RATES OF RISE, AND FIRST PEAKS, OF RESTRIKING VOLTAGE

1 and 2	3	4	5	6	7
Item and type of fault†	Stage in clearance†	Fault current cleared (kA)	Rate of rise of restriking voltage (V/microsec.)‡	First peak of restriking voltage (V)‡	Per pole (1) or per two poles (2)
(i) 3-phase-earth	Phase to phase-phase-earth	22·8	4 460	9 580	(1)
(ii) 2-phase-earth	Phase to phase-earth	19·0	3 660	8 000	(1)
(iii) Phase-earth	Phase to earth	0·95	180	400	(1)
(iv) 3-phase	Phase to phase-phase	22·8	7 320	13 900	(1)
(v) Phase-phase	Phase to phase	19·7	7 050	16 050	(2)

* See Fig. 12. Switch C clearing fault at or beyond H on group-busbar side of reactor.

† See Fig. 8.

‡ Measured by R.V.I. and adjusted for current.

eight alternators similar to No. 6 (on which the records were taken) are running on the busbars, that each of these is connected to the busbars by the same length of similar cable, and that the neutral earth resistance is connected to the star point of one generator, it is possible to obtain figures which represent running conditions fairly well.

The eight alternators in parallel will give a fault kVA

ampere, and first-peak voltage per kilo-ampere, as a single generator).

The 3-phase-earth and phase-earth cases were calculated, neglecting losses, on the basis of the phase-sequence impedance systems as set out in Appendix II; the 2-phase-earth case was obtained by an R.V.I. record taken on a dummy network set up to represent the appropriate phase-sequence impedance network [that

of Fig. 21 (iv)], on which calculation is rather difficult. Thus in Table 15 the figures of Rows (i) to (iii) take no account of losses, whilst those of Rows (iv) to (v) do so. The rates of rise of voltage are all quite low.

(c) Generating-Station Group Busbars

Table 17 shows rates of rise of voltage and first peaks calculated from Table 5 and from the two R.V.I. records taken, for the case of a circuit-breaker on a group busbar

Table 17

BREAKERS ON GROUP BUSBAR AT PRINCES POWER STATION, NECHELLS (SEE FIG. 12)*: COMPARISON OF R.V.I. MEASUREMENTS OF RATES OF RISE, AND FIRST PEAKS, OF RESTRIKING VOLTAGE PER KILO-AMPERE FAULT CURRENT, WITH VALUES DEDUCED FROM APPROPRIATE SYSTEM PARAMETERS, AND TABLE 1, COLS. 11-14

1 and 2	3	4	5	6	7	8	9	
Item and type of fault†	Stage in clearance†	From Table 1 and system parameters		R.V.I. record No.	From R.V.I. measurements		Per pole (1) or per 2 poles (2)	
		Rate of rise (V/microsec./kA)	First peak (V/kA)		Rate of rise (V/microsec./kA)	First peak (V/kA)		
<i>Neutral earth on supply side</i>								
(i) 3-phase-earth	Phase to phase-phase earth	184	425	None taken	156	190	9 600‡	(1)
(ii) 2-phase-earth	Phase to phase-earth	184	425				8 300‡	(1)
(iii) Phase-earth	Phase to earth	184	425	None taken	156	190	400	(1)
(iv) 3-phase	Phase to phase-phase	276	640				13 900‡	(1)
(v) Phase-phase	Phase to phase	368	850	155	357		16 000	(2)

* Breaker A clearing fault at B. For inherent rates of rise, etc., on group busbars, see Table 18.

† These figures are estimated from analogy with the R.V.I. records dealt with in Table 14.

† See Fig. 8.

Table 16 shows similar figures for a breaker on the main busbars clearing a fault just beyond a group-feeder reactor. These figures are obtained directly from R.V.I. records, and values of fault currents calculated from the actual kVA available in the Princes power station busbars during peak-load conditions. The low rate of rise

opening to clear a fault on an outgoing feeder. Here again the rates of rise per kilo-ampere are quite high. Table 18 shows the total rates of rise of voltage for the same circuit-breaker clearing a fault on its outgoing feeder. The rates of rise of voltage are again very high and may be taken almost as representing an upper limit

Table 18

BREAKERS ON GROUP BUSBARS AT PRINCES POWER STATION, NECHELLS (SEE FIG. 12)*: INHERENT RATES OF RISE, AND FIRST PEAKS, OF RESTRIKING VOLTAGE

1 and 2	3	4	5	6	7
Item and type of fault†	Stage in clearance†	Fault current cleared (kA)	Rate of rise of restriking voltage (V/microsec.)†	First peak of restriking voltage (V)†	Per pole (1) or per two poles (2)
(i) 3-phase-earth	Phase to phase-phase-earth	22.8	3 550	9 700	(1)
(ii) 2-phase-earth	Phase to phase-earth	19.0	3 020	8 000	(1)
(iii) Phase-earth	Phase to earth	0.95	180	400	(1)
(iv) 3-phase	Phase to phase-phase	22.8	7 300	14 500	(1)
(v) Phase-phase	Phase to phase	19.7	7 040	16 750	(2)

* Breaker A clearing fault at B.

† See Fig. 8.

‡ Measured from R.V.I. records and adjusted for current.

in the phase-earth case corresponds to the fact that, owing to the limitation of the current by the earthing resistor, a phase-earth fault is one of high power factor. Otherwise, the rates of rise of voltage are very high indeed: certainly one would not expect to encounter higher rates on an 11-kV system.

for British practice. Though the figures are high, they are not unexpected: Flurscheim,³ for instance, predicted rates of rise up to 4 000 volts per microsec. on such a system as is here considered; and Hameister¹⁵ gives the same figure as an upper limit for rates of rise on any system, irrespective of its voltage.

(8) BROAD CLASSIFICATION OF TYPES OF RESTRIKING-VOLTAGE TRANSIENT

If a number of circuit-breaker locations each yield the same inherent rate of rise of voltage, they may yet for convenience be divided into two separate classes. In one class, (a), the peak voltage reached at approximately the given rate is about 150 % to 200 % of the power-frequency peak voltage; whilst in the other class, (b), the peak value reached at the given rate is approximately equal to the power-frequency peak voltage.

Class (a) in general covers types of location where the fault kVA on the supply side of the last plant unit before the circuit-breaker location in question is more than, say, 3 or 4 times the fault kVA at the circuit-breaker concerned. This will cover most of the breakers on generating-station busbars, and on auxiliary busbars fed by single step-up or step-down transformers or through reactor banks giving a large reduction in kVA.

Class (b) includes all switchgear in substations fed by step-up and step-down transformers with an intermediate high-voltage line or cable, and all circuit-breakers on busbars fed from main busbars through group-feeder reactors.

(9) CONCLUSIONS

The outstanding conclusions reached in the present report are summarized below.

(a) The rates of rise of voltage encountered at the points investigated on the City of Birmingham 11-kV system range from 10 volts per microsec. to 7 500 volts per microsec., or, excluding phase-earth fault conditions (in which, in general, rates of rise are low by reason of the low phase-angle of the fault), from 230 volts per microsec. to 7 500 volts per microsec. The lowest rate (230 volts per microsec.) was associated with circuit-breakers on the generating-station main busbars clearing their full fault kVA, and the highest (7 500 volts per microsec.) with circuit-breakers on the generating-station group busbars clearing their full fault kVA, also with circuit-breakers on the main bars controlling group-feeder reactors, operating at about half their maximum kVA to clear faults on the group busbar.

(b) On circuit-breakers on 11-kV substation bars fed by step-down transformers from 33-kV transmission cables, a rate of rise of voltage of the order of 500 volts per microsec. appears to be typical (see Tables 10, 11 and 12). For indoor substations of normal layout it is not likely that rates of rise of voltage greater than about 1 000 volts per microsec. will be experienced. This figure might almost be taken as an upper limit for all locations on an 11-kV system with the exception of locations involving voltage-drops in air-cored reactors connected to switchgear by bare conductors mounted on insulators.

(c) Circuit-breaker locations yielding the same inherent rate of rise of voltage may broadly be divided into two main classes, depending on the ratio of the first peak of the fastest restriking-voltage transient there occurring, to the power-frequency peak voltage. Where the fault kVA, on the supply side of the last plant unit before the switch considered, is high compared with the fault kVA at the switch concerned, the first peak of re-

striking voltage arising under the worst fault conditions will be of the order of 1.5 to 2 times the power-frequency peak voltage. This applies, for example, to circuit-breakers on main busbars and to circuit-breakers on auxiliary busbars fed by single step-down transformers. Where the fault kVA on the supply side of the last plant unit is of the order of twice that of the switch considered, the first peak of the restriking-voltage transient will be of the order of the power-frequency peak voltage. This applies, for example, to circuit-breakers on busbars fed through group-feeder reactors, and to breakers in substations fed through feeders with transformers at each end.

(d) By the use of Tables 1 and 2 and the appropriate system parameters, it should be possible to estimate rates of rise of voltage at most circuit-breaker locations, the values so estimated being in the region of 20 % greater than the true value. Where there is doubt as to the appropriate parameters when making calculations on other systems, the power-frequency parameters will always give rates of rise, etc., still further in excess of their true values.

(e) In assessing circuit parameters, the following points should be noted:—

(i) When transformers determine the major frequency associated with a restriking-voltage transient, the capacitance per phase may usually be taken as the value obtained by multiplying the maker's declared capacitance per unit length by the length of cable per phase between transformer and switch. In cases where this capacitance is less than $0.025 \mu\text{F}$ per phase, an additional 0.002 to $0.005 \mu\text{F}$ should be allowed, to cover the self-capacitance of the transformer windings. The effective inductance per phase appears to be, for frequencies from 50 c./s. to 20 kc./s., about 100 % to 85 % of the inductance corresponding to the rated reactance of the transformer.

(ii) Where air-cored reactors determine the major frequency associated with a transient of restriking voltage, the effective inductance appears to be that appropriate to the rated reactance: this holds for frequencies so far examined up to 240 kc./s. Where cables connect the reactors to the circuit-breaker under consideration, the observation under (i) should apply: where the connection consists of bare conductor on insulators, it is probably necessary to calculate or measure the capacitance in each case.

(iii) Where generators are in question, the effective reactances per phase are considerably less than that equivalent to the rated (sub-transient) reactance of the machine: the reduction may be as much as 25 % to 50 %. There is as yet insufficient data on the subject to permit typical figures to be put forward.

(f) For most circuit-breaker locations it is only occasionally that a breaker clearing a fault is called upon to operate under conditions setting up the highest rates of rise of voltage possible at that location. This does not, however, apply to locations in which there are no other circuit-breakers teeing off the supply in parallel with the breaker in question.

(g) It is shown that the method of symmetrical components, as suggested by Monteith and Evans¹⁴ for phase-phase and phase-earth faults, can be readily

extended to the calculation of restriking transients under all types of fault conditions.

(h) In circuit-breakers operating on instantaneous relays, the type of fault giving the heaviest fault current broken and the highest rate of rise of voltage per pole of the circuit-breaker will in most cases be a 3-phase or 3-phase-earth fault. It is possible, however, that where the breaker operates with time-delay, the heaviest fault current cleared and the highest rate of rise of voltage will occur with a phase-phase-earth fault.

(10) ACKNOWLEDGMENTS

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APPENDIX I

Clearing of Busbar Faults on a System in which the Neutral Earth Point is Supplied by a Neutral-Earth Reactor

In a system such as that of Fig. 18, where the neutral earth point for the substation busbars is supplied by a

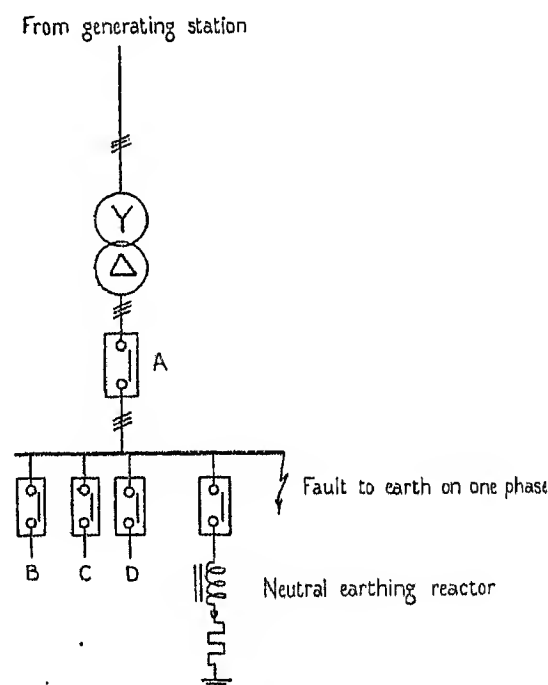


Fig. 18.—Breaker A clearing fault to earth on one phase, with fault current in all three phases of breaker.

neutral-earthing reactor, the method of earthing introduces some complication into the consideration of the manner in which faults are cleared. Fault currents in

circuit-breakers on feeders such as B, C and D can be calculated in the normal manner, and their interruption proceeds on the same lines as on a system with an earthed star point in the supply. A 3-phase-earth fault, for instance, becomes successively a phase-phase-earth fault and a phase-earth fault, as the currents on the poles of the 3-phase circuit-breaker are interrupted in turn.

Conditions for the circuit-breaker A are, however, somewhat different, since the breaker will only carry positive and negative phase-sequence currents, and the interruption of faults involving the earth connection proceeds in consequence in a somewhat different manner.

For any phase-earth fault the fault currents can be calculated by considering the phase-sequence impedance networks connected as shown in Fig. 19(a). For a system such as that here considered, however, the various networks are as shown in Fig. 19(b), if we assume that for the supply and load systems $Z_1 = Z_2 =$ (say) Z and Z_l respectively. The total current carried by the switch A (Fig. 18) is the sum of the currents in the branches marked S in Fig. 19(b). Whilst evaluation of this total current in general terms of the various impedance components gives an expression which is too complicated for use here, there is no difficulty in calculating numer-

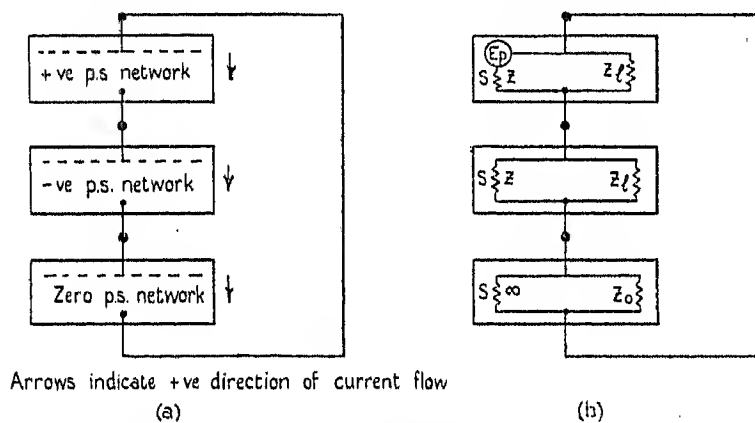


Fig. 19.—Arrangement of phase-sequence impedance networks giving fault current in Breaker A, Fig. 18.

ically the fault current in the switch for any given system, and Fig. 20 shows the currents in the three phases of the switch for the system constants relating, for instance, to Switch A at Bangor Road (Fig. 9). These currents include the currents supplied to the load under fault conditions, the total load being taken as 10 000 kW at 11 kV, unity power factor.

Since there are currents flowing in all three phases, it is clear that the interruption of the phase-earth fault cannot take place in one operation. It appears probable that the smallest current will be cleared first, and then the current in the remaining phases, from the following considerations:—

The smallest current i_b (Fig. 20) is substantially equal to $E/(Z + Z_l)$, whilst the currents in the other two phases are each of about twice this value. The impedance of the system, viewed from a point of entry at any one of the poles of the circuit-breaker concerned (A, Fig. 18), can be shown to be approximately $3(Z + Z_l)/2$, the earthed phase making no appreciable difference. Since the recovery voltage on interrupting a current I r.m.s. amperes flowing in a system of Z ohms impedance is IZ r.m.s. volts, then:—

For phase (a) broken first, recovery voltage $\simeq 3E_p$;

For phase (b) broken first, recovery voltage $\simeq 3/(2E_p)$;

For phase (c) broken first, recovery voltage $\simeq 3E_p$;

where E_p is the system phase voltage.

Thus for i_a or i_c clearing first, the pole of the switch concerned would have to stand a recovery voltage of approximately $3E_p$, whilst for i_b clearing first, the switch would have to stand a recovery voltage only $3/(2E_p)$. It thus appears strongly probable that with any practical circuit-breaker i_b would clear first, more especially since it can be shown that the rate of rise of voltage when i_b clears first is considerably less than the rate of rise when either of the other two phases clears first.

The currents in phases (a) and (c) are of course equal and opposite at the instant at which the current in

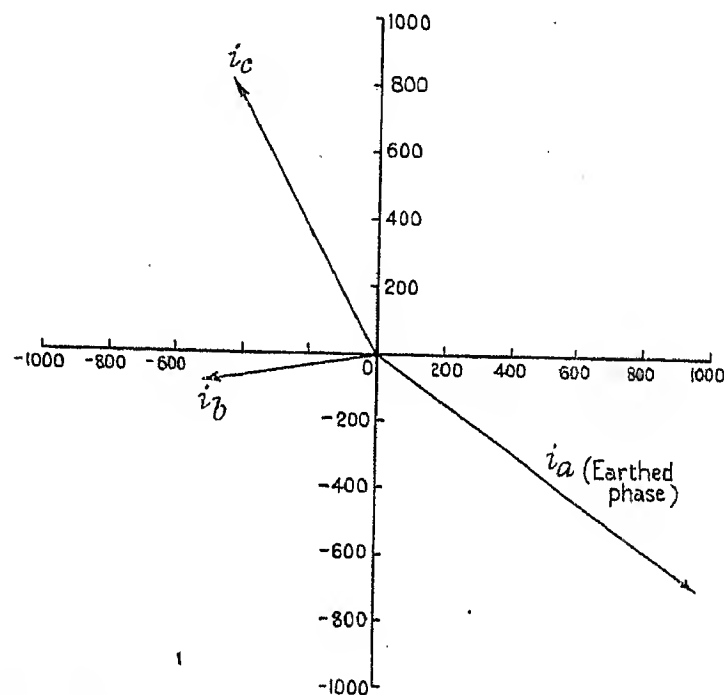


Fig. 20.—Currents in three poles of breaker supplying busbar on which there is a fault to earth, when neutral earth is given by neutral-earthing reactor connected to busbar.

phase (b) is interrupted, but they have not then the value appropriate at that instant under sustained conditions with phase (b) open-circuited; this value is approximately $\frac{\sqrt{3}E_p}{2(Z + Z_l)}$ taken at the proper phase.

The current in these two phases must therefore decline by a transient from the value under normal fault conditions to the value under fault conditions with phase (b) open-circuited.

In the case of a phase-phase-earth fault on the busbars, the switch A (Fig. 18) carries fault current in all three poles, as in the case of a phase-earth fault. The fault currents in the three phases can be calculated in a manner similar to that described for the phase-earth case; it will be found that the current in the unearthed phase is quite small. If the unearthed phase clears first, the recovery voltage across that phase is $1.5 E_p$, whilst if either of the other phases clears first the recovery voltage will be $\sqrt{3}E_p$. The unearthed phase also has to contend with a considerably lower rate of rise of re-striking voltage than either of the other two phases. Thus it is extremely probable that when the switch A (Fig. 18) attempts to clear such a fault, the unearthed

phase will clear first, and then the two earthed phases simultaneously.

The interruption of a 3-phase-earth fault will proceed in the same manner whether or not the neutral-earthing reactor is connected, since the reactor is continually short-circuited by the fault.

APPENDIX II

Effective Reactance of a Generator and its Influence on the Clearance of Different Types of Fault

To calculate the transient of restriking voltage at the clearance of different types of fault supplied by a generator it is necessary to know the effective reactance of the generator to the particular change postulated by the clearance of the fault. These reactances are defined by

This agrees with the value deduced from the appropriate R.V.I. record (see Table 4, Row 4). At the interruption of the first phase of a 2-phase-earth fault, the reactance should be

$$x \times \frac{(1 + 2n)}{(2 + n)} = x \frac{1.84}{2.42} = 0.49 \text{ ohm}$$

(No R.V.I. record was taken in this connection.) At the interruption of a phase-earth fault the reactance should be

$$x \times \frac{(2 + n)}{3} = x \frac{2.42}{3} = 0.52 \text{ ohm}$$

This agrees with the value deduced from the appropriate R.V.I. record (see Table 4, Row 3).

Table 19

EFFECTIVE REACTANCE AT THE INTERRUPTION OF DIFFERENT STAGES OF DIFFERENT TYPES OF FAULT, IN TERMS OF REACTANCES TO SYMMETRICAL COMPONENTS

1	2	3	4	5
Type of fault and stage of clearance	Voltage appearing across pole of switch	Current interrupted	Effective reactance	Effective reactance if $nx_1 = nx_2 = x_0^*$
1st phase of 3-phase fault	$3E_p x_2 / (x_1 + x_2)$	E_p / x_1	$3x_1 x_2 / (x_1 + x_2)$	$1.5x_1$
2nd phase of 3-phase fault	$(a^2 - a)E_p \dagger$	$(a^2 - a)E_p / (x_1 + x_2)$	$x_1 + x_2$	$2x_1$
1st phase of 3-phase-earth fault	$3E_p x_0 x_2 / \sum x_0 x_1$	E_p / x_1	$3x_0 x_1 x_2 / \sum x_0 x_1$	$x_1 \cdot 3n / (n + 1)$
2nd phase of 3-phase-earth fault	$E_p [(a - 1)x_2 + (a - a^2)x_0] \dagger$	$E_p [(a - 1)x_2 + (a - a^2)x_0] \dagger$	$\frac{\sum x_0 x_1}{\sum x_0}$	$x_1(1 + 2n) / (2 + n)$
3rd phase of 3-phase-earth fault	$\frac{(x_1 + x_2 + x_0)}{E_p}$	$\frac{\sum x_0 x_1}{3E_p / (x_1 + x_2 + x_0)}$	$(x_1 + x_2 + x_0) / 3$	$x_1(2 + n) / 3$

E_p = phase voltage. x_0, x_1, x_2 = reactances to symmetrical components of current.
 $a = -0.5 + 0.866j$.

* Substitution valid under transient conditions.

† These values apply to one phase (say B phase). The other phase (say C phase) will have different current and voltage values, but same effective reactance.

† This voltage appears across two poles.

the ratio between the voltage appearing across the pole of the circuit-breaker interrupting the current, and the current interrupted. It is known that the reactance varies with the type of fault cleared, and it is here shown how the various effective reactances may be deduced from a knowledge of the positive, negative, and zero phase-sequence reactances of the generator.

In Table 19 are set out, for each stage of interruption, the voltage appearing across the break (Col. 2), the current interrupted (Col. 3) and the ratio between these two quantities, giving the effective reactance of the machine to the particular interruption (Col. 4). So far as transient conditions are concerned, it is possible to unite $nx_1 = nx_2 = x_0$, where n is some constant; and Col. 5 gives the effective reactances in terms of x and n , i.e. the effective reactances during transient conditions.

These relations agree with the numerical values given in the body of the report: for instance, from the R.V.I. records treated in Table 4 we find that in the phase-to-phase and phase to phase-phase cases $x = 0.65$. In the 3-phase-earth case $nx = 0.27$, or $n = 0.42$. At the interruption of the first phase of a 3-phase-earth fault the reactance should be

$$x \times \frac{3n}{2n + 1} = x \times \frac{1.26}{1.84} = 0.44 \text{ ohm}$$

APPENDIX III

Application of Method of Symmetrical Components to Calculation or Measurement of Transients of Restriking Voltage under any Fault Conditions

It has been shown by Evans and Monteith¹⁴ that the method of symmetrical components can be applied to the evaluation of transients of restriking voltage for phase-phase and phase-earth fault conditions. It is not difficult to extend this to cover all types of fault conditions.

It has been shown in Appendix II that the reactances of a system to the clearance of the first and second two phases of a 3-phase fault and the first, second and third phases of a 3-phase-earth fault are respectively $3x_1 x_2 / (x_1 + x_2)$; $(x_1 + x_2)$; $3x_1 x_2 x_0 / (\sum x_1 x_2)$; $\sum x_1 x_2 / (\sum x_1)$; and $(x_1 + x_2 + x_0) / 3$.

Diagrams showing how the phase-sequence impedance networks are connected to give these resultant impedances are shown in Fig. 21.

Since when we are dealing with transients of restriking voltages, positive and negative phase-sequence impedances can always be taken as equal, the diagrams of Fig. 21 can be simplified as shown in Fig. 22. It will be clear that, once the systems giving rise to the transients

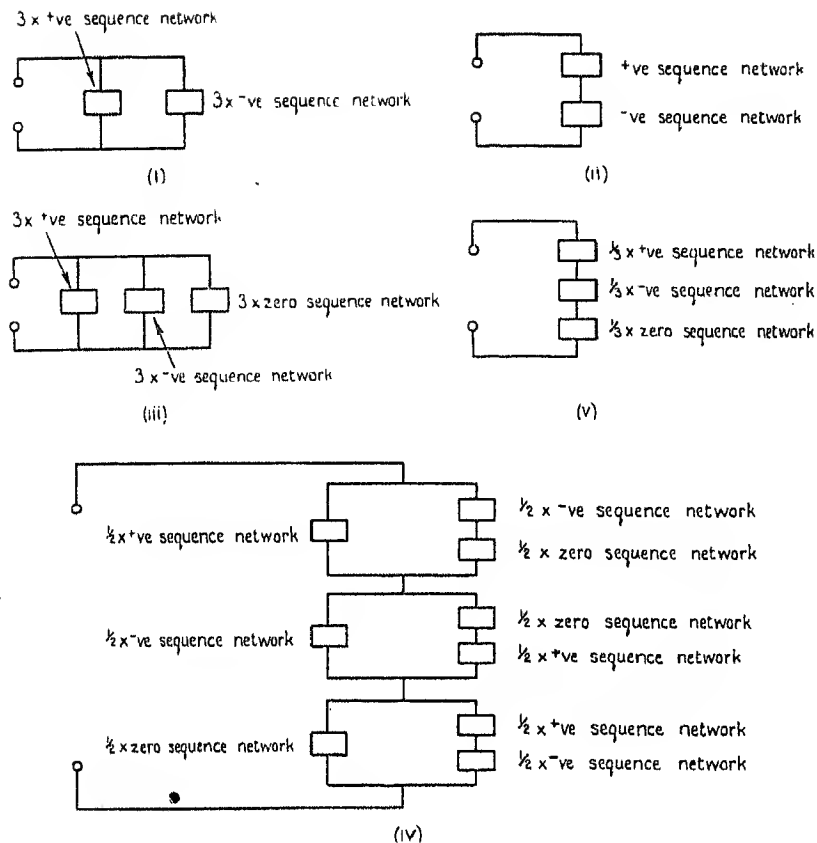


Fig. 21.—Interconnection on phase-sequence impedance networks to represent effective impedance of systems at clearance of different types of fault. ("1/2 x +ve sequence network" represents the impedance of two positive-sequence networks in parallel.)

- (i) Impedance at clearing of first phase of 3-phase short-circuit.
- (ii) Impedance at clearing of second two phases of 3-phase short-circuit.
- (iii) Impedance at clearing of first phase of 3-phase-earth short-circuit.
- (iv) Impedance at clearing of second phase of 3-phase-earth short-circuit (first phase of 2 phase-earth short-circuit).
- (v) Impedance at clearing of third phase of 3-phase-earth short-circuit.

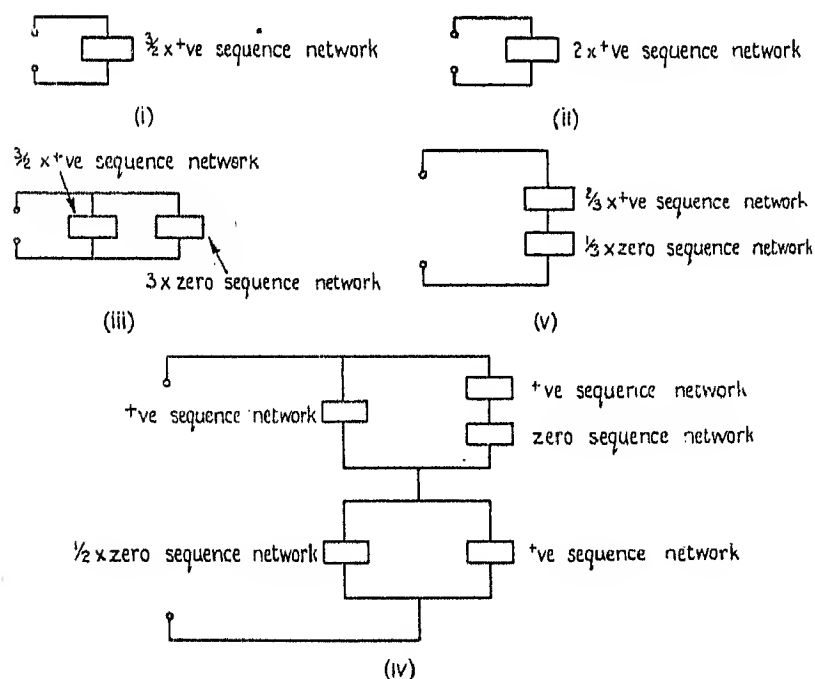


Fig. 22.—Arrangements of phase-sequence impedance systems to give transients of restriking voltage at clearance of different types of fault.

- (i) System determining transient at clearance of first phase of 3-phase short-circuit.
- (ii) System determining transient at clearance of second two phases of 3-phase short-circuit.
- (iii) System determining transient at clearance of first phase of 3-phase-earth short-circuit.
- (iv) System determining transient at clearance of second phase of 3-phase-earth short-circuit.
- (v) System determining transient at clearance of third phase of 3-phase-earth short-circuit.

of restriking voltage in the positive and zero phase-sequence systems have been established, it is possible to deduce therefrom the transients in all other types of fault interruption.

From Fig. 22 it will be seen that whereas for (i), (ii) and (v) (clearances of both types of unearthed fault, and phase-earth fault) the transients of restriking voltage contain only those frequencies appearing in the positive and zero phase-sequence systems alone, transients at the other two types of clearance (first and second phases of a 3-phase-earth fault) must in general contain quite new frequencies.

APPENDIX IV

Note on Effective Reactance of an Alternator so far as Transients of Restriking Voltage are Concerned

The variation of effective reactance with time arises from the fact that the leakage-flux paths determining this reactance are in the main paths through iron or

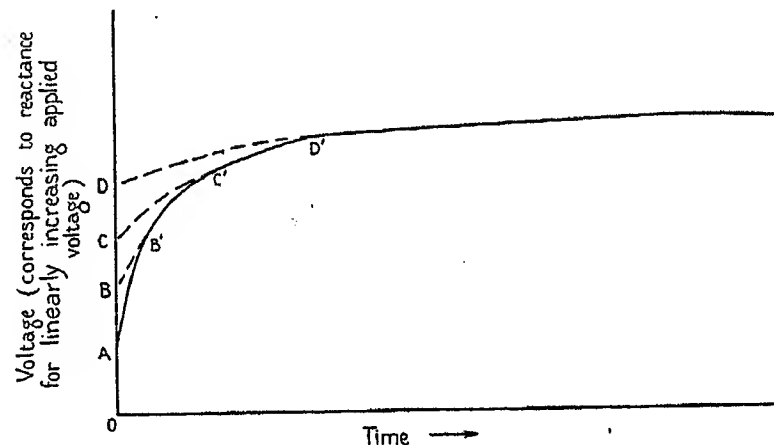


Fig. 23.—Form of voltage across two terminals of generator with zero self or external capacitance, to which a linearly-increasing current starting from zero is applied.

copper, so that on any change of current through the windings the flux is prevented from changing with the current, by reason of eddy currents in flux paths. In the complicated structure of an alternator, eddy-current paths of diverse time-constants exist. One, in the field winding, determines the rate at which the effective reactance of the machine increases from the transient to the synchronous value (this time-constant may be of the order of 1 sec.). A second set of eddy-current paths, of time-constant of the order of 0.02–0.05 sec., determines the rate of change of effective reactance of the machine in the sub-transient stage. C. E. R. Bruce¹³ has, from a study of recovery voltage, shown the existence of components of time-constant less than 0.01 sec. It must follow that there exist components of time-constant of the order of 100 microsec. determined by eddy currents in the stator iron stampings and in the copper windings themselves. Thus a linearly increasing current forced through the generator windings (as would be possible only in the absence of winding capacitance) would experience a voltage of the form shown by the full line in Fig. 23. The value OA is determined by a reactance appropriate to those leakage paths through air only. The voltage thereafter increases in a series

of exponential terms appropriate to the various eddy-current paths.

Attempts to deduce the initial reactance from data on which the earliest valid points are B', C', D', etc., will result in obtaining the values OB, OC, OD, etc., all greater than the true initial reactance OA. Thus when we attempt to obtain a value for this initial reactance from considerations of the amplitude of an R.V.I. record, the value obtained will vary to some extent with the frequency of its oscillatory component, which determines the time of the earliest point on a curve such as that of Fig. 23. Such a value, however, is sure to be less than the "sub-transient reactance" of the generator calculated from its percentage reactance, since the latter is determined from consideration of power-frequency phenomena only.

On account of the capacitance of the windings and external cables connected, the restriking-voltage transient contains an oscillatory component also. The "reactance" to this component of current, whilst it starts at OA (Fig. 23), rapidly settles down to a value appropriate to its frequency. This value will be somewhere between OA and the final value. Thus if from

considerations of the known external capacitance of the cables with the self-capacitance of the windings, and the frequency of the oscillatory component of the transient, an effective reactance is deduced, it is likely that this reactance will be different from that deduced from amplitude considerations with the R.V.I. as described above.

The phenomena described above can easily account for the apparent excessive damping frequently observed in the first cycle of transients of restriking voltage across a generator.

The variation (with the type of fault cleared) of effective reactance per phase, even to transients of restriking voltage, is due to difference between positive or negative and zero phase-sequence sub-transient reactance. The effective reactance per phase at the interruption of any type of fault can be expressed in terms of the various phase-sequence reactances as shown in Appendices II and III: thus from knowledge of the positive and zero phase-sequence reactance per phase it is possible to calculate an effective reactance per phase at the clearance of any type of fault. This probably applies to capacitance, although the point has not been checked.

IRISH CENTRE: CHAIRMAN'S ADDRESS

By THOMAS A. McLAUGHLIN, B.E., M.Sc., Ph.D., Member.*

(Address delivered at DUBLIN 25th January, 1940.)

The history of civilization is one of constant change in the conditions of living from generation to generation. These changes occur in peace time by a gradual process of development due to the continuous effort of the community to improve conditions. Constructive effort is the vocation of the engineer—in constructive achievement he finds happiness. The catastrophe of war which has burst upon the world has called a momentary halt to construction. Change will now be brought about mainly by the forces of destruction. The engineer must adapt his activities and his outlook to the new surroundings. It would be idle to pretend that, as engineers, our predominant thoughts are still engaged in the particular spheres of electrical science which are our all-absorbing interest in peace time. We are in reality much more concerned with the new world which will result from the convulsions through which society is now passing. The catastrophe of war and the economic difficulties which it brings in its train have turned men's minds back to fundamental thoughts. We are more concerned at present with considerations of our place in, and our duty to, society. It is a time for stock-taking—we are entering into a new era. It is a time to look back to consider what our contribution as engineers has been to progress in the past, and to look forward to consider how our profession can make the better contribution to society for which the more difficult future will call.

How important is the place of the engineer in society? Of what relative consequence is the contribution he makes to the community? These are matters to which, as engineers, we rarely, if ever, give thought. We are generally too much concerned with the details of our day-to-day constructive work. At a time such as the present when circumstances compel us to give thought to these matters, we are ourselves somewhat surprised to realize of what great consequence our activities are to the progress and welfare of the community. Yet, as a profession, we are little heard of in the public life of the community. We have little to say to the direction of the world in which we live, yet we do much to bring about the changes in it. When we give some consideration to the matter, we come to realize that the material welfare of the community has been largely altered by the engineer and is to-day largely dependent on the efficiency of the engineering profession. In the present time of crisis it is of prime importance that the profession should consider the grave implications of this serious responsibility to society.

Through the ages the human species has remained the same; the elementary requirements of man in mind and body have remained the same. What has altered is

what might be termed the mechanical organization of civilization. The primitive needs of man are still food, clothing and shelter. But science and engineering have altered in time, out of all recognition, the ability of man to satisfy these needs in quality and quantity. The discoveries of science, by which man has been enabled to apply the huge forces of energy contained in Nature to the problem of production—where he was previously limited by the energy which the human or animal alone was capable of expending—have been the main factors which have contributed to material progress. In the future, as in the past, the ability to provide food, clothing and shelter in better quality, greater quantity and at less cost, will depend on the application of scientific study and knowledge to the problems of production and on the application of mechanical machinery to production itself. The main factors which have influenced material progress in this century are all discoveries of science and engineering, the development of the applications of electricity, and improvements in communications.

What contribution has engineering made to material progress in this young State of ours? At the period of the establishment of the State, some 20 years ago, war and strife had left the country in a backward condition so far as the amenities of modern civilization were concerned. It was then not a State which called primarily for new invention and discovery to bring about progress. It is hardly even in such a condition to-day. What was required was to endeavour to achieve quickly a state of material progress comparable with that which existed in more developed lands. What was required was not scientific research so much as practical engineering. The business of the engineer was to study development as it existed in other countries, to study methods of design and construction, to study economy in materials and to apply existing knowledge to the rapid development of this country. Only as we tend to achieve a state of material development comparable with the most advanced lands will new invention and discovery make its appearance here. The relatively backward state of the country rendered rapidity in development the primary need. How far has this been achieved and what factors will influence, or are influencing, its future achievement?

The main spheres of development in which the profession of electrical engineering in this country has been engaged are the activities of the Department of Posts and Telegraphs and the electricity supply industry. In the Chairman's Address last year we were told of the former activities. It remains for me, therefore, to speak of the progress of the electricity supply industry.

Development of electricity supply on a large scale in this country began just a decade ago when the hydro-

* Electricity Supply Board of Eire.

electric plant of the River Shannon went into operation in October, 1929. At that time there were two major power plants—one in Dublin City and one in Cork City—and throughout the rest of the country there were in many of the towns small local plants supplying mainly electricity for lighting purposes. In the area surrounding the centre of the present City of Dublin, electricity supply mains were limited to the immediate suburbs of Rathmines and Pembroke and the centre of Dun Laoghaire. Large towns such as Waterford, Sligo, Tralee, Wexford and Drogheda, with populations varying from 27 000 to 11 000, were without electricity supply. The plant installed at Pigeon House in Dublin had a capacity of 21 000 kW, while that in Cork City amounted to 7 700 kW. The peak load at the Pigeon House station was 17 250 kW, while that at the Cork station was 4 300 kW. The total electricity sold in the country for public electricity supply purposes amounted to 48 million units in the year prior to October, 1929. Of this, 31 million were sold in Dublin City and its immediate suburbs of Rathmines and Pembroke. In Cork City 9 million units were sold, including supply for tramway purposes. The residue of only 8 million units represented the total sales throughout the rest of the country. The use of electricity throughout the rest of the country was confined practically completely to lighting. Over half the consumption in Dublin City and suburbs was for lighting and domestic supply, the residue of some 13 million units being for motive-power purposes. The total number of electricity consumers in the country was 50 500, of which 26 000 were in Dublin City and its immediate suburbs and 4 200 in Cork City, leaving some 20 000 throughout the rest of the country.

The corresponding figures relating to the present state of electrical development are mainly contained in the statistics of the Electricity Supply Board. The power plant now installed on the Pigeon House site has a capacity of some 80 000 kW, which the extra unit just installed will bring up to 100 000 kW. The peak load of Dublin City is now about 48 000 kW and that of Cork City about 9 500 kW. The total electricity sold for public supply purposes (excluding traction) amounted to 276 million units, as against the 48 million units a decade ago. The sales in the former Dublin City area, with its immediate suburbs of Rathmines and Pembroke, would amount to some 107 million units, as compared with the figure of 31 million. The sales for motive-power purposes in this area would amount to some 35 million, as compared with the figure of 13 million. The sales in Cork City area were 24 million units, as compared with 9 million, while the residual sales throughout the rest of the country amounted to 145 million units, as compared with the figure of 8 million units a decade ago. Of these sales, some 65 million were for motive-power purposes, an all-important purpose in the material progress of the community for which public electricity supply was in fact, as indicated, not available a decade ago. The total number of electricity consumers had increased over the same period from 50 000 to 160 000, of which 74 000 were in the Dublin City area and its immediate suburbs and 11 000 in Cork City.

In glancing at the increase in the number of electricity consumers in Dublin City area from 26 000 to 74 000 over the decade, it is necessary to check up on the in-

crease in population so as to get a correct appreciation of the percentage of potential consumers connected. The population according to the 1926 census was 409 000, and had increased to 476 000 on the records of the 1936 census. Taking account of the average number of persons per family, the percentage of families in Dublin City area using electricity had risen from some 27 % of the total to 67 % over the decade. The population of Cork City was 92 000 in 1926, and 99 000 in 1936. The number of electricity consumers was, as stated, 4 200 in 1929 and had increased to 11 000 in 1939. The percentage of families using electricity increased from 20 % to 49 %.

It is of interest to glance at the similar progress in some of the urban areas. The population of Limerick City increased from 41 000 to 44 000, and the number of electricity consumers from 885 to 6 461. Galway City increased from 14 000 to 18 000 in population, while the number of electricity consumers increased from 897 to 2 431. Dundalk increased in population from 14 000 to 16 000, with an increase in electricity consumers from 985 to 2 168. Clonmel increased in population from 9 000 to 9 400, while the electricity consumers increased from 177 to 671. All these were areas supplied by small local plants a decade ago.

The criterion of the general increase in the number of electricity consumers from 50 000 to 160 000 is interesting as an indication of the degree to which a supply of electricity is available to, or used by, the community. Another criterion is the total population of the areas served by electricity distribution mains. This amounts to some 1 200 000. The total population of the country is, however, some 2 900 000, leaving some 1 700 000 population living in territory yet unserved by electricity mains. These are the agricultural population living in dwellings scattered all over the country, and we are aware of the very difficult problem it is to make progress in supply to such scattered dwellings.

In considering the general question of advance in electricity supply, the most striking criterion is the increase in sales of electricity. Excluding for the moment the sales in Dublin and Cork cities, the increase in the remainder of the country has been, as stated, from 8 million units to 145 million units over the decade. In Limerick City the increase was from 970 000 to 8 400 000 units; in Galway City from 430 000 to 4 080 000 units; and in Dundalk from 1 167 000 to 3 800 000. Omitting these areas, the increase in sales for the remainder of the country has been from $5\frac{1}{2}$ million units to 129 million units over the decade.

An analysis of the increase in sales under various headings is of interest. An accurate figure for the sale of electricity to domestic consumers a decade ago is not readily available, but it was of the order of 10 million units as a total for the whole country. The corresponding figure in 1939 was 84 million units. Outside the domestic sales, the sales of electricity for general heating, cooking and water-heating reached the figure of 27 million in 1939, whereas in 1929 the sales for these purposes were negligible.

The consumption per consumer of electricity for domestic purposes has now reached a reasonably advanced figure compared with that in other countries.

In Dublin City environs, which is probably the most well-to-do residential area in the country, it has reached the average figure of 1 200 units per consumer; in Dublin City area 650 units per consumer, and in Cork and Limerick cities about 550 units per consumer. Over the rest of the country it would be about 750 units per consumer.

The sales of electricity for industrial motive-power purposes in the year prior to the Shannon plant coming into operation totalled 20 million units for the whole country—a decade later they had reached the figure of 115 million units. Of this 20 million units, 13 million units were sold in Dublin City and its immediate suburbs, 5 million units in Cork City, and not more than 2 million units in the rest of the country. The corresponding figures a decade later were 35 million units in Dublin City, 15 million units in Cork City, and 65 million units in the rest of the country. The total industrial horse-power connected to public electricity supply amounted in 1929 to some 25 000 h.p.—a decade later this figure had risen to 108 000 h.p.

The great increase in consumption of electricity for industrial motive power in the areas outside the two large cities is of particular interest as indicating a spread of industrial activity throughout the country following the spread of electricity-supply mains. There are published in the Appendices to the Annual Reports of the Electricity Supply Board since 1932, tables showing the industrial horse-power connected in each city, town and village, and a study of these tables will give a very good appreciation of the growth in use of electricity for industrial motive-power purposes throughout the country. It is of particular interest to note the growth in the small towns and villages, where electric motors are now largely being used to do work which could previously only be done by hand.

The figures set out are sufficient to show that remarkable progress has been made in the electricity-supply industry in this territory of ours over the last decade. I do not propose to try to give any picture of the development of the huge machine that has been built up to achieve this progress, or to try to give any conception of the engineering work that has gone into the achievement. What we started out to do was to glance at the achievement itself and to check up on our contribution to society. But while figures of increase in plant capacity, peak load and units sold, do convey to us that we have made remarkable progress, I have often wondered just how much they convey to the man in the street, or indeed how far they convey to us, as engineers, the real contribution we are making to the material progress of the community. For instance, what is the importance of the fact that the sale of electricity for industrial motive-power purposes has increased from 20 million units to 115 million units over the last decade? Its importance is that production can only be achieved by the expenditure of energy, and electricity is a form of energy. The increase in units sold means, therefore, that we have made available to the community so much additional energy to assist in increase of production. How really great the contribution has been, however, we can only realize if we glance for a moment at the worth of a unit of electricity as a form of work and

compare it with the work which a man can do himself in a day working with his muscles. In this respect it may not be out of place to quote from an article published in the June, 1939, issue of the American *Edison Electric Institute Bulletin*, entitled "When You Buy Electricity You Buy Work." The work is done in the power house down by the river, is transmitted by wire all over the country, and is used in the homes and factories of the community. In this article the fundamental fact was stressed that "No man can make a unit of electricity in a day with his muscles alone." Engineers have measured in foot-pounds or work units the work that all kinds of labourers can do in a day, and their day's muscle work averaged only 28 % of a kilowatt-hour. It has been established that "a unit of electricity is equal to the muscle work of a man pumping for 2 days, lifting weights for about 5 days, hammering for about 6 days, carrying a hod for about 7 days, wheeling bricks for about 8 days, or shovelling for about 9 days." When we contemplate these facts, we realize how "man's muscle work and power is puny, no matter what the task." We realize also what a great contribution we make, as electrical engineers, to man's productive capacity when we provide him with units of electricity to do work previously done by hand. An endeavour to express the present annual sale of 115 million units of electricity for industrial motive power purposes in man-days of work gives a much better appreciation of the contribution they represent to the efforts of the community. They are equivalent to the muscular effort of about $1\frac{1}{4}$ million men working for a year.

Increased sales of electricity are accordingly of great importance to the community in so far as they really mean the provision of labour for production at a minimum cost. No human working with his muscles can do more than a fraction of the work in a day that a unit of electricity can be made to do, and no human could exist on wages which would compete in cost with a unit of electricity. Whether we like it or not, we have, as a community, to eke out our existence in a world where production is largely mechanized, and if this particular community of ours is to maintain a standard of living in keeping with even the present-day stage of world material progress, then it must have at its disposal modern means of production. As electrical engineers engaged in the electricity-supply industry, our contribution to social progress has been to place mechanical energy in its cheapest and most pliable form, namely electricity, to as widespread a degree as possible, at the disposal of the community.

But what of the future? Is the community which has at present electricity supply at its disposal utilizing it to the full, and what of the large and very important section of the community which has not as yet any supply of electricity at its disposal? As regards the first section of the community, we can answer straight away, from our knowledge of the experience of our colleagues in other countries, that our community has really only begun in the last decade seriously to avail itself of electricity supply and that its use of it will, and must, increase very rapidly if the community itself is going to progress in material prosperity. I do not propose, in

this Address, to labour this argument—it is so fundamental a truth as not to require further proof at the moment. But what of the large section of the community to whom, as engineers engaged in the electricity supply industry, we have not as yet succeeded in bringing supply? In the present state of world progress, can this section of the community reach a modern standard of living unless modern engineering science is brought to their assistance to a much greater degree? Personally I cannot see how they can, and I feel that, as engineers concerned with our duty to the community, we shall have seriously to turn our thoughts to this problem.

The mass of the population to whom electricity supply is not as yet available are those living in the truly rural areas and mainly engaged in agricultural production. They are that section of the population from which comes the social evil of "the flight from the land," an evil which is a great source of worry to our community. They are at the same time that section of the community wherein lies the primary necessity for increased and cheaper production. Can "the flight from the land" be diminished or stopped unless the standard of living in these rural areas is brought closer to the level of that in the towns? I think we must agree it cannot. And can the standard of living in the rural areas be raised otherwise than by the application to a greater degree of modern science and engineering? I think we must also agree it cannot. And can cheaper and increased production be achieved by an increased use of man and animal muscle-energy only? It can perhaps to a limited degree, but I cannot see how it can be brought to anything like a competitive level without the use, at least to a corresponding degree, of the modern mechanical means of production used in the more prosperous agricultural countries of the world. We must not overlook the fact that electricity supply is at the disposal of, and is utilized to a high degree by, the rural and farming communities of such kindred agricultural countries as Denmark and Sweden. Is not one of the reasons why farming in this country gives such a poor return to the farmer and worker engaged on the farm, as compared with the worker engaged in production in the towns, the fact that, whereas the farmer must rely for his output practically completely on muscle effort, the worker engaged in the towns has abundant and very cheap labour to assist him in the form of mechanical power or work placed at his disposal by the utilization of the forces of nature—"the work done in the power house down by the river"? Let us again recall that one unit of electricity, costing a few pence, can yield more work than any one man can do in a day!

The problem of the extension of electricity supply to the rural community is one very difficult of economic solution, and it is not made easier by the general economic difficulties of the present situation. It is mentioned simply to indicate to the engineer that, while he can take pride in present achievements, there remains a big field for effort and a further major contribution which engineering science must make to the progress of the community. Effort on the part of the engineer

results in achievement, not when the technical problems are solved, but only when the solution found serves the primary purpose of better economy. The fact that the problem is difficult of economic solution renders it none the less a problem for engineers—a problem for the economic solution of which the community must turn to the engineering profession.

To return to the general question of the place of the engineer in, and his duty to, the community, there is one very serious aspect of activity which at this critical period appears to me to call for special consideration. We are passing into more difficult times, a period in which the community cannot afford to tolerate waste effort, a period in which results must be achieved with a maximum of efficiency and a minimum of expenditure. Yet, as engineers, we cannot close our eyes to some aspects of a growing inefficiency in community effort. If you agree with me that this situation does exist, you will also agree with me that I should be failing in my duty if I did not call attention to it at this critical time. As engineers our whole *raison d'être* is to increase the efficiency of community effort; the purpose of our education and training is to enable us to bring to the aid of the community the great sources of power in Nature. We can equip ourselves with all this knowledge, we can be possessed of all the capacity, but the results achieved will be little if the community does not find ways and means to utilize our service effectively, and I feel that at the present time there is a very clear tendency for the community machine to develop in such a manner as to reduce rather than add to its efficiency.

As engineers, we should not be surprised at this tendency—it is a natural development arising out of the growing complication of communal activities. It is a tendency for which there is a clear parallel in the development of electricity distribution itself. As a system of electricity distribution grows and spreads out, as the load grows, the necessity for increased protective equipment here and there on the system constantly arises, but it is not uncommon to find, with the growing complications of the system, that the protective measures taken from time to time have grown to such a complicated system of protection as no longer to serve their purpose with any degree of efficiency. The engineer then finds it necessary to re-examine the problem as a whole, to scrap the complicated protective system and introduce a much simpler solution, relating any risks in operation to the primary purpose of an economic and efficient service to the consumer.

I venture to suggest that there is a similar tendency in the community machine and that it must be corrected to secure greater economy and efficiency in effort in the more difficult times ahead. It is only because I feel deeply the necessity for maximum economy and efficiency in community effort that I mention the matter at all, and only because I feel that to permit inefficiency in effort to develop would not only be an injury to the community, of which we are all members, but would be disastrous to the progress of our own profession.

INDUSTRIAL APPLICATIONS OF ELECTRICITY*

By H. G. WEAVER, Member.

The progress which has been made in the applications of electricity in iron and steel works is the outstanding feature of factory electrification since the publication of the last review of progress in 1936,[†] and it therefore forms a considerable proportion of this review. The electric driving of steel rolling-mills and their auxiliaries has, however, not been dealt with, as this is to be the subject of a separate paper.

ORE UNLOADERS

It appears to be now established that whereas Ward-Leonard control affords the most efficient method of providing the drive for the hoist and long travel motions, the additional weight involved in the carrying of the conversion set on the crab is considered to outweigh its advantages, and a plain direct-current series drive has proved the most popular, the motors being, of course, of the steel-clad mill pattern, with roller bearings and split frames.

COAL HANDLING

The main point of interest with recent installations of drives for coal-handling plant is the universal adoption of totally enclosed, fan-cooled motors, which are described later in this review. The controls have a system of sequence interlocking, which ensures that the stopping of certain conveyors will always automatically ensure the stopping of any other conveyors that are feeding it.

COKE-OVEN PLANT

More attention has recently been paid to the enclosure of the motors used in these plants, owing to the deleterious effect of the gases in the atmosphere. Special castings are used as far as possible, care being taken to see that they are free from porosity. Gas-proof gaskets and varnish are used for all frame and cover joints, and the windings carefully sealed with varnish and given extra coats of enamel.

BLAST FURNACES

Modern practice in the electrical equipment of blast-furnace skip hoists is shown by the following particulars of a recent installation for two hoists.

The hoists are of the balanced type, with two hoist motors on each. The weight of each bucket empty is 12 000 lb., and the weight of ore charge 18 000–20 000 lb. The skip travel is 200 ft., at a speed of 450–600 ft./min., with an angle of incline 53° from the horizontal. Each hoist is driven by two 200-h.p., 220-volt, direct-current, steel-works-type motors, with a speed range of 0–570–762 r.p.m. by shunt control, which are forced-ventilated by motor-driven blowers mounted on top of the motor

frame. A 24-in. solenoid brake is mounted on the driven shaft. The two motors are connected in series across a 310-kW, 440-volt generator.

The two skip hoists are arranged by switching to run from any two of three motor-generator sets, each set comprising a 310-kW, 440-volt generator driven by a 450-h.p., 3-phase, slip-ring induction motor.

The control of the hoists is by contactor gear, with hand-operated master switches. Track-limit switches, over-wind limit switches, screw-gear depth indicators, and landing-speed adjusting rheostats, are all provided.

New features are continually being introduced in the electrical operation of the winch equipment for the charging bells of blast furnaces. In a recent example the large bell is driven by a 17-h.p. d.c. compound-wound motor, and the small bell by a 10-h.p. motor of the same type and speed. In each case the motor speed when raising the bell is 540 r.p.m., and when lowering the bell 840 r.p.m. The control is by contactors and resistances, and is so arranged that in the event of slack cable the bell-lowering contactors are opened and the winch is automatically reversed, so taking up the slack cable; then after a short time interval the bell is automatically caused to lower again, and this operation is repeated until the bell falls away freely or the operation is tripped by hand. The slack-cable switch is operated from the sealing-weight balance lever. There is also complete interlocking of the bells, such that one bell must have completed its full travel and also sealed before the other bell moves.

The production of iron in a modern blast furnace is a continuous process, and the main essential of furnace operation is therefore smooth and regular working, with as few stops as possible. The most difficult problem has been the development of a satisfactory method of stopping up the iron tapping hole when required, without the necessity of shutting off the blast.

An electrically-driven clay gun has recently been introduced for this purpose, the motors being of a special design, as described later. The gun itself is suspended from a boom, which swings it into position and holds it against the hole while plugging is taking place. The gun is driven by a 20-h.p. motor, and the boom by a 10-h.p. motor. Both motors are of the 3-phase induction type with squirrel-cage rotors. They are switched direct on to the line, without any overload or other type of protection, but limit switches are provided on both motions to prevent mechanical damage due to mal-operation of the controllers. The stalling torque of the 20-h.p. motor is 1.6 times full-load torque, and of the 10-h.p. motor 1.35 times full-load torque, in each case when taking 2.5 times full-load current at full line voltage. The boom motor is stalled when holding the

* A review of progress.

† *Journal I.E.E.*, 1936, 78, p. 333.

gun against the hole, and the gun motor may be stalled if the hole is small. Very high ambient temperatures are encountered, and the motors have to be capable of withstanding stalling for half a minute under these conditions without excessive heating. They are of welded steel construction throughout, and have 3% nickel-steel shafts running in ball and roller bearings. The stator windings are insulated with asbestos in mica-lined slots. The rotor windings consist of bronze bars secured in semi-enclosed slots, which are lined with anodized aluminium. The short-circuiting end rings are of heavy-section eureka metal, these being slotted to receive the rotor bars, and the whole brazed together at high temperature. This method of construction combines high heat capacity with high resistance.

ELECTRIC FURNACES

For melting both ferrous and non-ferrous metals, high-frequency furnaces and arc furnaces have been installed in increasing numbers, but very considerable developments have taken place in electric furnaces for heat treatment since the last review was published. They are now used in the production of castings, sheets, strip and wire, for normalizing, stabilizing, and particularly for bright annealing.

One plant for producing aluminium sheets has been equipped with a soaking pit furnace for ingots, a chain conveyor furnace for slabs, cylindrical pit furnaces for coil annealing, and salt-bath furnaces for the heat treatment of sheets, all electrically heated and capable of dealing with aluminium.

A particularly interesting development which is gaining ground more and more is the nitriding process, i.e. the treatment of special steel in an ammonia atmosphere, for the production of specially hardened parts. This zone-hardening can now be accomplished in 3 to 7 seconds, the cost of power being very small compared with the results obtained.

High-frequency induction furnaces are also being used for many operations where quick and uniform heating is required. Round steel bars, $2\frac{3}{8}$ in. diameter, can be heated ready for forging in 90 seconds.

Electric furnaces are now used to a greater extent in the ceramic industry, for firing all kinds of ceramic wares and glaze firing of earthenware and porcelain in special electric kilns.

ELECTRIC WELDING

One of the latest applications of electric welding is the production of nickel-clad steel plate, in which nickel sheets are welded on either side of a steel slab and the whole is rolled out to a large plate. The welding in this case ensures correct location of the two metals until the rolling process has thoroughly welded them together.

A new electric welding process is now being used in which heat is generated by the passage of the current from an electrode, through a highly resistant material, to the work. The resistant material is in granulated form, and is placed along the seam to be welded and also fed to the end of the electrode. The latter is of bare metal, and as the entire action takes place beneath the resistant material without an open visible arc it is not necessary for the operator to wear a shield. Intense

concentrated heat is generated within the layer of resistant material, and a portion of the edges being welded is melted and fused. During welding, a sub-surface layer of molten resistant material floats as a liquid over the molten weld metal and excludes the atmosphere and other gases, thus making a clean, dense metal of excellent physical properties. A fine-wire fuse is used to start the weld.

GENERATING PLANT

In factories which generate all or part of their requirements, the unit or non-basement type of turbo-generator for small and medium outputs is now usually installed. The arrangement consists of a high-speed turbine running at about 6 000 r.p.m., geared to a generator running at about 1 000 r.p.m., with the extraction pump driven mechanically from, and the circulating pump coupled direct to, the low-speed shaft. The condenser is also arranged on the same floor-level.

Results obtained with a number of installations during recent years show conclusively that where large quantities of process steam are required in a factory, in addition to electric power, the use of a back-pressure or pass-out turbo-generating set will enable power to be generated at an almost absurdly low cost, especially where good balance between the heating and electrical requirements can be arranged.

SWITCHGEAR

Main Switchgear

In large factories the control of the bought or generated electric power has emphasized the importance of adequate rupturing capacity of main switchgear under modern conditions, and the segregation of plant to minimize fire risk. Manufacturers have been giving much attention to the design of switchgear, with a view to reducing the quantity of oil and inflammable compound necessary, and the latest types of switchgear of a given rupturing capacity now contain only a fraction of the quantity of such materials required by switchgear of the same capacity a few years ago. These remarks apply especially to the larger breaking capacities. Circuit-breakers of the air-blast type are now attracting much attention.

Distribution Switchgear

The rupturing capacity of low-voltage a.c. switchgear has also become of increasing importance, owing to the larger sizes of transformer now frequently used; and low-voltage oil switches have definite limitations in this respect.

In factories containing much inflammable material, the risk of fire has led to the development of air-break switchgear of a rupturing capacity up to 50 MVA at 660 volts, 3-phase; this is also satisfactory on direct-current systems.

Increasing use is being made of high-rupturing-capacity fusegear for the protection against short-circuits of distribution circuits to small motors, heating and lighting. They are used not so much for overload protection as against faults, the motors having their own overload protection in their starters, but the latter need not be, and rarely are, capable of withstanding short-circuits on the system, the high rupturing-capacity

fuses dealing with these, and thus saving apparatus. Another valuable feature of this type of fuse is that it does not deteriorate with time.

The group-drive line-shaft system is being rapidly displaced by self-contained motor-driven machines, and in machine shops which have a large number of such machines the distribution of power to them becomes difficult, especially when it is not convenient to run cables on the floor or under it. To meet such conditions, overhead busbar systems have been developed and are now widely used. The system consists of tubular or rectangular bar conductors carried on porcelain or moulded insulators, with steel trunking for supporting and enclosing the conductors and arranged for securing to the roof or roof members. The busbar chambers are so arranged that circuits can be teed off easily by means of fused units, which in some designs can be plugged in.

There is now available an almost indestructible type of cable for use in difficult situations where standard types of cable give trouble. It consists of copper conductors which are embedded in an insulating mineral powder compressed under heavy pressure in a copper tube. It will withstand great heat and severe mechanical damage, the insulation remaining good at very high temperatures and up to the point of fracture if hammered out flat.

MOTORS

The large volume of air passing through modern screen-protected motors necessitates frequent cleaning of the machines unless the air is very clean, and the most notable development of recent years is the increased use of totally enclosed, fan-cooled a.c. machines.

In the smaller sizes the cooling is obtained by fitting a cowl over one end-bearing bracket, and a fan fixed on the shaft inside the cowl blows air over the outer surface of the frame, which is usually ribbed to assist cooling.

In the larger sizes an external fan circulates air through ducts formed in the outside of the stator frame, and an internal fan circulates the internal air to ensure an even cooling effect inside the machine.

There are also now available totally enclosed, fan-cooled d.c. motors with outputs up to 200 h.p., the cooling system consisting of a special cast-aluminium diaphragm which encloses the motor at the driving end, and which is itself enclosed by a bearing bracket of the standard screen-protected type. The bearing bracket at the commutator end is of the totally enclosed type. External and internal fans are used, the exchange of heat taking place through the aluminium diaphragm.

Under very bad conditions, such as log grinders in paper mills, where even large air passages would get choked, the pipe-ventilated type of enclosure is still used, supplied with clean air. In dairies, where swilling down with hose-pipes takes place, motors are now used with special watertight enclosures. In gas works, chemical works, and other factories where atmospheric conditions are very bad, special gasproof enclosures are used, as described earlier in this review.

Improvements in the design of squirrel-cage motors to obtain increased starting torque still continue, and 3-phase motors are now made which give full-load torque at starting, when taking 1.6 times full-load

current. Single-phase repulsion-induction type motors are now available which give 3.5 times full-load torque, taking 2.5 times full-load current at starting when switched direct on to the line.

Motors subject to rapid reversal, where high starting torque is also required, such as the drives for some modern machine tools, are a special problem. They are usually controlled by switching direct on to the line, with severe short-circuit conditions when reversing. A very high temperature occurs in the machine, which is created by motor performance, as distinct from motor load, and increasing the size of machine only leads to increase in temperature. Under these conditions, varnished and bakelized glass fibre has been used for insulation.

Extra-high-speed motors for driving woodworking machines have been developed, and a.c. motors with speeds up to 6 000 r.p.m. when used with frequency changers are now being made. Very much higher speeds have been obtained, and the limiting factor appears to be bearing design, not electrical.

For variable-speed drives, the d.c. motor with shunt field control is still mostly used, but when direct current is not available the a.c. commutator motor is becoming more popular. Ward-Leonard control is also being adopted more frequently for drives where its inherent ability to give full-load torque at creeping speeds is of value.

CONTROL GEAR FOR MOTORS

The outstanding feature of motor control is the modern tendency to adopt automatic contactor gear, mainly to obviate breakdowns due to careless or inaccurate handling by unskilled labour, and also because of its adaptability for remote control.

Push-button-operated, contactor type, star-delta and direct-to-line starters for a.c. motors up to 25 h.p. are now produced in large quantities, at prices which compare favourably with hand-operated types. There is still a difference of opinion with regard to the respective merits of magnetic and thermal type overloads, although the latter is becoming more widely used.

When the direct-to-line type is used and frequent "inching" of the motor is required, some designs are not satisfactory, as they are not capable of rupturing the short-circuit current of the motor. In recent years there has been much research by manufacturers into the design of blow-out coils and arc shields to improve the performance in this direction, and this problem may be said to have been solved by some of them.

A new system of timing the acceleration steps of automatic contactor starters has been developed, utilizing a condenser-charge neon-tube discharge circuit. The neon tube is of a special rugged type and operates, in sequence, control circuit relays for each acceleration step. The timing circuit has great flexibility of adjustment and great accuracy, and is particularly suitable for applications in which the flywheel effect of the load requires longer periods of acceleration than are obtainable with the usual types of relay.

Another new system of acceleration control for d.c. starters utilizes the time taken to discharge a condenser connected across the closing coil of a relay which energizes the accelerating contactors. The timing is adjusted

by varying the magnetic gap of the relay, is very accurate, has no moving parts, and is independent of load or temperature conditions.

In order to obtain a predetermined acceleration/torque curve with a slip-ring type a.c. induction motor, it is necessary to cut out resistance in the rotor circuit at the correct speeds. A new frequency relay has been developed for this purpose which operates on a resonant circuit and is responsive to the slip frequency of the rotor. The relay is extremely accurate, and it is also used to provide a quick stop by plugging the motor at a predetermined speed.

Photo-electric equipment is now extensively used for automatic timing operations, counting, etc., in many industries. The new neon capacitance timing-device previously mentioned is also found very useful when a timing limit for a given process is required, within limits up to 10 minutes. It is provided with a grid leak to give a definite time-delay action, and the delay can be modified by altering the value of the grid leak.

A new design of direct-current generator for battery-

charging equipments has been developed which possesses novel characteristics and does not need a reverse-current cut-out. This design has an unconventional form of magnetic system, and there are no series turns on the pole-pieces. For charging small batteries the constant-potential system, which imparts a tapering charge and gives automatic protection against over-charging, is accepted as being the best practice. A normal compound-wound generator designed to produce a level voltage characteristic between no load and full load is not suitable for this duty without the use of a reverse-current cut-out, since in the event of failure of supply to the driving motor the generator would receive reverse current from the battery and either run at an excessive speed as a motor or stall, the heavy discharge current causing a reversal of polarity. In the event of a failure of supply to the driving motor for the new design of generator, the set will continue to run at approximately full speed, taking a small current from the battery. When the supply is restored, the set resumes charging and there is no tendency for reverse polarity to occur.

AN EXPERIMENTAL INVESTIGATION OF RESONANCE AND ELECTRONIC OSCILLATIONS IN MAGNETRONS*

By J. S. McPETRIE, Ph.D., D.Sc., and L. H. FORD, M.Sc., Associate Members.

(Paper received 26th June, 1939.)

SUMMARY

The paper describes an experimental investigation of the oscillations produced by magnetrons. It is shown that in all types of magnetron valves, oscillations are possible for which the ratio of the product of wavelength and anode voltage to magnetic field has a series of discrete values given by the series

$$K : K/2 : K/3 \dots K/n$$

in which K is a function of the anode diameter. Oscillations at frequencies corresponding to values of n up to 7 have been observed. In a full-anode magnetron all the oscillation intensities are small. For a 2-segment-anode magnetron the amplitude of the oscillation of lowest frequency ($n = 1$) is pronounced; in a 4-segment-anode magnetron oscillations at the frequency corresponding to $n = 2$ are predominant, and so on. These oscillations all belong to the class known as resonance oscillations. It is shown that there is no clear distinction between resonance and electronic oscillations at very short wavelengths, and it is suggested in the paper that they are essentially of the same nature.

(1) INTRODUCTION

The magnetron oscillator as a source of high-frequency radiation has been known for many years, but there is still no completely satisfactory explanation of its very complex behaviour. The wavelength obtained is dependent on the form of the anode of the valve, the nature of the external circuit, the anode voltage applied, and the strength of the magnetic field used. Oscillations can be classified into a number of types according to the relationships which hold among these quantities. At present, at least three such types of oscillation are recognized in magnetrons.^{1,2}

(A) Electronic Oscillations.

These oscillations occur near the so-called critical value of magnetic field where the anode current decreases rapidly with increase in magnetic field intensity. It has been found empirically that the product of wavelength (λ) in centimetres and magnetic field (H) in oersteds is a constant of about 11 000.^{3,4,5} The frequency of electronic oscillations, in general, is higher than the fundamental resonant frequency of the smallest external circuit which can be attached to the valve, and the external circuit, which is usually in the form of Lecher wires, must be adjusted in length so that an overtone resonance coincides in frequency with the frequency of the oscillations. It is generally observed that the maximum amplitude of electronic oscillation occurs with relatively low filament

emission.⁶ Electronic oscillations have been found in single- and multi-anode segment magnetrons.

(B) Dynatron Oscillations.

Near the critical magnetic field in a split-anode magnetron a simple negative resistance condition is obtained suitable for the production of oscillations at the resonant frequency of any circuit connected across the anode segments. With a fixed anode voltage the optimum value of magnetic field is independent of the wavelength of oscillation.

(C) Resonance Oscillations.

These oscillations are similar to electronic oscillations in that the frequency is dependent on the operating conditions of the valve, but they are found not only near the critical magnetic field but at all values of magnetic field greater than the critical value. For a given valve the wavelength of resonance oscillations is proportional to the ratio of magnetic field to anode voltage. It has been suggested² that there is no clear line of demarcation between resonance and electronic oscillations.

Since the magnetron is primarily of interest as a source of power at very short wavelengths most investigators have concentrated their attention on this aspect of the problem. For very short wavelengths, however, all types of oscillations occur near the critical field, and much of the confusion into which the study of the magnetron has fallen is due to this fact. It is only when the wavelength is greater than about 5 metres that separation between the condition for the dynatron and resonance types of oscillation is possible. On these relatively long wavelengths no electronic oscillations are possible and the resonance oscillations occur at magnetic field intensities much greater than the critical field, at which the dynatron oscillations are still obtained.

In order to overcome the difficulties in differentiation between dynatron and resonance oscillations in multi-segment valves, and also to enable observations to be made on all the types of oscillations at approximately the same wavelength, the authors have made a number of measurements with the conditions adjusted so as to make the oscillation amplitude in these valves as small as possible. In this way the range of magnetic field (the most common variable) over which the oscillations occurred was limited. The measurements were made on valves with a full cylindrical anode and also with 2- and 4-segment anodes, and were directed towards determining the circumstances under which oscillations could be obtained rather than to finding the conditions for greatest efficiency.

* Official communication from the National Physical Laboratory.

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(2) EXPERIMENTAL PROCEDURE AND RESULTS

(a) Full-anode Valve

The dynatron type of oscillation is not possible with a magnetron valve which has a single cylindrical anode, and it is generally assumed that only oscillations of the electronic type occurring near the critical field and satisfying the $\lambda H = \text{constant}$ law can be obtained with such valves.⁷ Experiments made at the National Physical Laboratory with a full-anode valve showed, however, that oscillations could be produced with magnetic field intensities much greater than the critical value and with various values of λH . There is considerable

magnetic field up to the greatest magnetic field available and that the wavelength, in any particular case, did not necessarily obey relation (1). For the same magnetic field, oscillations at two or even three wavelengths were sometimes present simultaneously, the wavelengths bearing usually some simple relation to one another, such as 1:2, 2:3. Results are shown in Fig. 1 in which for an anode voltage of 540 the wavelengths of the oscillations are plotted as ordinates against the corresponding values of magnetic field as abscissae. It will be seen that the oscillations occur at magnetic fields much greater than the critical value shown by the vertical dotted line in the

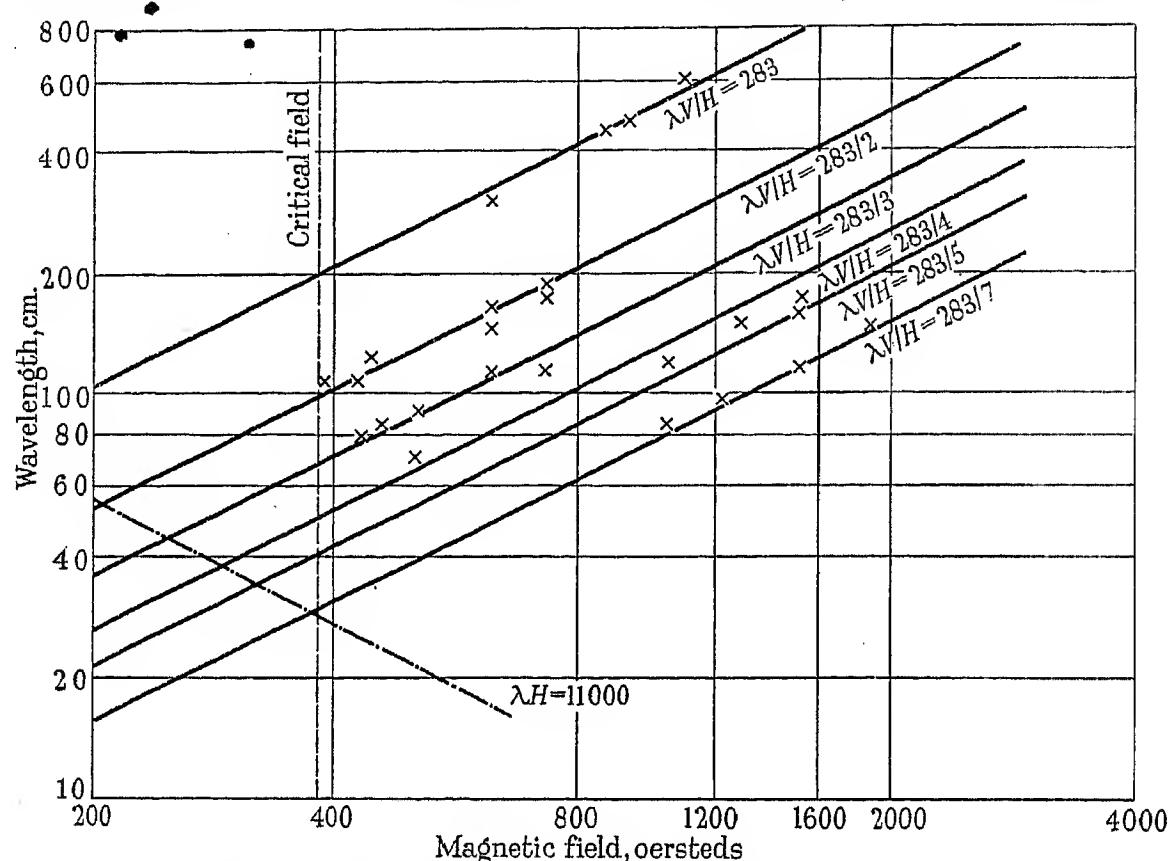


Fig. 1.—Wavelength of oscillations of full-anode magnetron.

$V_a = 540$. Anode diameter = 1 cm. (nominal).

difficulty in devising a satisfactory external circuit for a full-anode valve. A Lecher wire system connected to anode and cathode and terminated by a capacitance of a few micro-microfarads was tried, but it was found that both the wavelength and amplitude of the oscillations were independent of the length of the circuit. No observable difference was obtained by varying the positions on the circuit of the points at which the H.T. supply to the magnetron was connected.

The anode voltage in each series of tests was kept constant, and the magnetic field, provided by an electromagnet, adjusted until oscillations were detected by means of a diode rectifier coupled closely to the circuit. According to the accepted hypothesis for the production of oscillations in single-anode-segment magnetrons these oscillations occur only near the critical magnetic field and their wavelength is such that

$$\lambda H = 11\,000 \quad (1)$$

It was found,* however, that for each anode voltage oscillations could be obtained from about the critical

* It is of interest to note that Okabe⁸ states he has also found oscillations at a magnetic field greater than the critical value. He gives few details, however, and only one experimental result.

figure, and that the experimental points lie closely to a series of parallel lines given by

$$\frac{\lambda}{H} = \frac{\text{const.}}{n}; n = 1, 2, 3, \text{ etc.} \quad (2)$$

As mentioned above, oscillations at two or three frequencies were obtained, but usually the different oscillations occurring at one magnetic field intensity could be differentiated by suitable adjustment of filament emission. For example, with a magnetic field intensity of 1 040 oersteds an oscillation at a wavelength of 83 cm. was observed with full filament current of 6 amperes; when the filament current was reduced to 5.7 amperes this oscillation disappeared and was replaced by an oscillation at 118 cm. wavelength. On further reduction of filament current, this oscillation ceased and, with only slight readjustment of magnetic field, oscillations at 610 cm. were obtained.

A point of considerable interest is that although the most careful search failed to detect any normal electronic oscillations complying with the condition $\lambda H = 11\,000$ near the critical value of magnetic field, the line given by relation (2) with $n = 7$ cuts the line corresponding to the

critical field at the same point as the broken line in Fig. 1 and given by relation (1). This result was not peculiar to this experiment. Although anode voltages ranging from 120 to 600 were used, in no case were electronic oscillations of the usual type observed. In all cases, however, where a sufficient number of oscillating conditions were obtained to enable a series of lines to be drawn as in Fig. 1, the line given by $n = 7$ cut that corresponding to the critical field at the point at which electronic oscillations should have appeared according to other observers.⁷

Results similar to those shown in Fig. 1 were obtained with other anode voltages, the positions of the parallel lines altering in such a way that for a given wavelength the ratio of anode voltage to magnetic field intensity remained constant. The slope of the lines in Fig. 1 is such that for each line $\lambda/H = \text{constant}$, so that as H for a given wavelength λ is proportional to the anode voltage V , $\lambda V/H = \text{constant}$. The values of $\lambda V/H$ for a series of anode voltages are given in Table 1; they correspond to the lines having respectively the maximum and minimum observed values of $\lambda V/H$.

Table 1

Anode voltage	λ	Magnetic field	$\frac{\lambda V}{H}$
	cm.	oersteds	
300	590	560	315
	140	1 040	40
360	500	640	280
	98	840	42
480	480	820	280
	145	1 580	44
600	580	1 120	310
	115	1 600	43

The average maximum and minimum values of $\lambda V/H$ from this Table are respectively 296 and 42. The ratio of these two numbers is about 7, showing that for a given magnetic field there was a ratio of 7 in the range of wavelengths of the oscillations obtainable.

(b) Two-Segment Magnetron

Both dynatron and resonance oscillations can readily be obtained with a two-segment magnetron at relatively long wavelengths (5 metres and upwards), but at lower wavelengths, as pointed out above, it is difficult to differentiate between the two types. It has been shown¹ that the relation between the wavelength λ (cm.) of the resonance oscillations, the magnetic intensity (H) in oersteds, and anode voltage (V) is given by

$$\frac{\lambda V}{pd^2H} = 430 \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

in which d is the diameter in cm. of the anode and p the number of pairs of anode segments (equal to unity in a 2-segment valve). The experimental fact that the operating conditions must be adjusted for each particular

wavelength suggests that there must be some form of resonance within the valve, whence the name applied to the oscillations. Experimental evidence of this resonance has been given,² and an equivalent electrical circuit deduced for a magnetron in the neighbourhood of these resonance oscillations. The resonance found in magnetrons is similar to that observed in the case of an electronic oscillator of the positive-grid triode type. The electronic oscillations obtained near the critical magnetic field in a magnetron have the same characteristics as those found in the positive-grid triode, both being due to pronounced inter-electrode transit time effects. The critical magnetic field of a magnetron having an anode diameter of d cm. is given by

$$\frac{d^2H^2}{V} = 180 \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

This relation, combined with the empirical result $\lambda H = 11\,000$, can be combined to yield the relation

$$\frac{\lambda V}{d^2H} = 61 \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

It will be noted that relation (5) is of exactly the same form as relation (3) for resonance oscillations when p in the latter expression is made equal to unity, but that the ratio of the values of the two factors is almost exactly 7. It is interesting to note in passing that this number represents the range in value of $\lambda V/H$ obtained with the full-anode magnetron and given in Table 1. If, as suggested,² resonance and electronic oscillations are essentially of the same form some explanation of the apparent discrepancy between the two experimental results represented by relations (3) and (5) is required. The chief distinction between resonance and electronic oscillations in any magnetron for a given anode voltage is the wavelength of the oscillations, the resonance wavelength being, in general, many times greater than the electronic. The wavelengths used by Gill and Britton¹ to determine relation (3) were of the order of 40 metres, while the wavelength of the electronic oscillations from which relations (1) and (5) have been derived has usually been of the order of 20 to 30 cm. Experiments were made, therefore, to determine whether the constancy of $\lambda V/H$ observed in the previous measurements at the longer wavelengths was maintained over the whole possible range of wavelengths, or was, in fact, a function of the wavelength of the oscillations. If the latter result was obtained, then in view of the previously shown similarity between resonance and electronic oscillations they could well be the same type of oscillation occurring at different wavelengths.

A 2-segment magnetron was connected to an external circuit consisting of a variable condenser and a series of plug-in coils. The wave-range covered in this way was from about 1.5 to 40 metres. The experimental procedure was to set the circuit to the desired wavelength and to vary the magnetic field without alteration of anode voltage until oscillations were detected by means of a diode rectifier coupled closely to the magnetron. The magnetic field was then adjusted until the oscillation intensity was a maximum, and the filament current was reduced until the oscillations could just be detected. These two adjustments were not, in general, completely

independent of one another and the procedure had to be repeated several times before the optimum field at the lowest possible filament current could be determined. The filament current was reduced in this way so as to limit the amplitude of the oscillations and thus make it possible to differentiate between the different forms of oscillation by preventing any overlapping between them.

The results of a series of measurements made in this way are shown in Fig. 2, from which it will be seen that the results are somewhat complex. The straight line A corresponds to the dynatron oscillations occurring near the critical magnetic field. Since this field is dependent only on the anode voltage applied to the valve and not on the wavelength of the oscillations, one would expect, as shown experimentally, the points to lie on a straight

the resonance oscillations on curve R. If the amplitude of oscillation was large these two maximum output conditions merged into one at an intermediate value of magnetic field. There appears to be no doubt, however, that the value of $\lambda V/H$ for resonance oscillations with a given valve does decrease with decrease in wavelength.

Results similar to those plotted in Fig. 2 have been obtained with a number of anode voltages and with various angles between the valve axis and the direction of the magnetic field. In each case the same general type of curve was obtained, the effect of an increase in tilt being to lessen somewhat the curvature of the $\lambda/(\lambda V/H)$ curve at short wavelengths.

In Fig. 2 the magnetic fields required for dynatron and resonance oscillations are shown; experiments were also

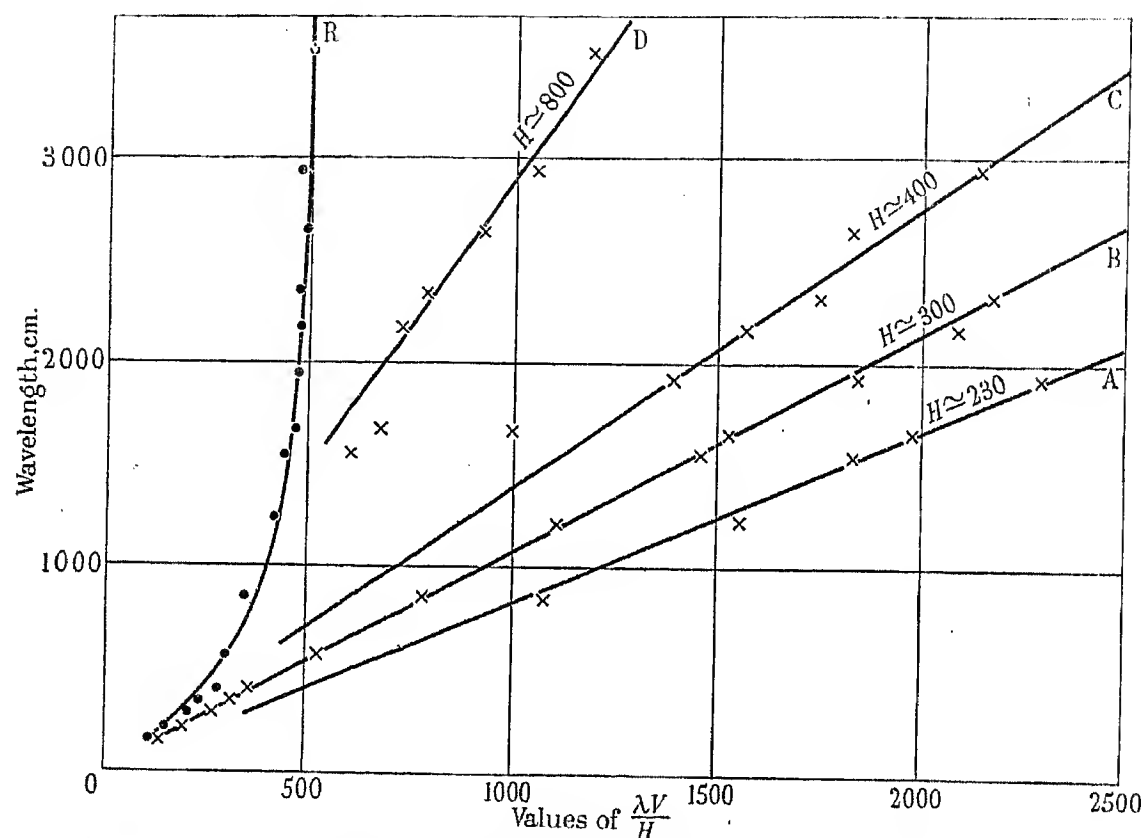


Fig. 2.—Wavelength plotted against $\lambda V/H$ for 2-segment anode magnetron.
 $V = 300$ volts. λ in cm., V in volts, H in oersteds.

line passing through the origin. In addition to the line A a number of other straight lines radiating from the origin were obtained. These lines represent oscillations which occur at certain values of magnetic field greater than the critical value but which appear to be of the dynatron type since the wavelength corresponds to the fundamental frequency of the external circuit, and the magnetic field at which they occur is independent of the wavelength. The resonance oscillations are shown by the curve R from which it is evident that although the value of $\lambda V/H$ is a constant for the longer wavelengths it decreases gradually for low values. At the shortest wavelength it was difficult to differentiate between dynatron and resonance oscillations, since a very small change in the current in the magnetizing coils was sufficient to alter the oscillating condition from one form to the other. By keeping the filament current small, however, it was usually possible to distinguish two peaks of oscillation output as the magnetic field intensity was changed. One maximum output condition corresponded to the dynatron oscillations on line A and the other to

made to determine whether, in addition to these, unclassified oscillations could be obtained at any wavelength at a magnetic field greater than that required for resonance oscillations at that wavelength. Such oscillations were found, although their amplitude was in general extremely small. The wavelengths of the oscillations are shown in Fig. 3 plotted as ordinates against the corresponding magnetic fields as abscissae for an anode voltage of 600. The curve for the usual type of resonance oscillations again shows a decrease of $\lambda V/H$ with diminishing wavelength for small values of the latter. Lines, similar to those shown in Fig. 1 for the single-anode valve corresponding to values of $\lambda V/H$ equal to $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, $\frac{1}{5}$, and $\frac{1}{7}$ of the final magnitude of that quantity for long-wavelength resonance oscillations, have been drawn in the Figure. It will be seen that there is a distinct tendency for the oscillations to lie on these lines. It is of special interest to note that the electronic oscillations ($\lambda H = 11\,000$) occurred on the one-seventh line. This raises the possibility that for these weak oscillations, of which the electronic may be a special case, the 2-segment valve

behaves in the same manner as a full-anode valve. The values of $\lambda V/H$ for the top lines in Figs. 1 and 3 are respectively 280 and 450. The valves had each a nominal diameter of 1 cm., but the measured critical magnetic fields were such that the ratio of the effective diameters was actually 1.18. Assuming in accordance with (3) that $\lambda V/H$ is proportional to the square of the anode diameters, $(450/280)^2$ should be equal to 1.18. Its actual value is 1.27, which is near enough to 1.18 to give support to the hypothesis that the series of values of $\lambda V/H$ in both full-anode and 2-segment-anode valves are identical for valves of the same dimensions.

The results shown in Figs. 2 and 3 establish that the

of values close to 11 000, especially at high anode potentials. In addition, a few scattered values of about 6 000 were noted at low voltages as reported by Okabe,⁹ and values of 22 000 also occurred.

(2) The wavelength with any particular valve did not vary smoothly with anode voltage. Certain definite wavelengths would appear with two or three different values of anode voltage and then be replaced by other widely different wavelengths. This effect has been observed also by other workers.³

(3) Oscillations obeying the electronic law $\lambda H = 11\,000$ were not confined exactly to the critical magnetic field but occurred at field intensities both greater and smaller

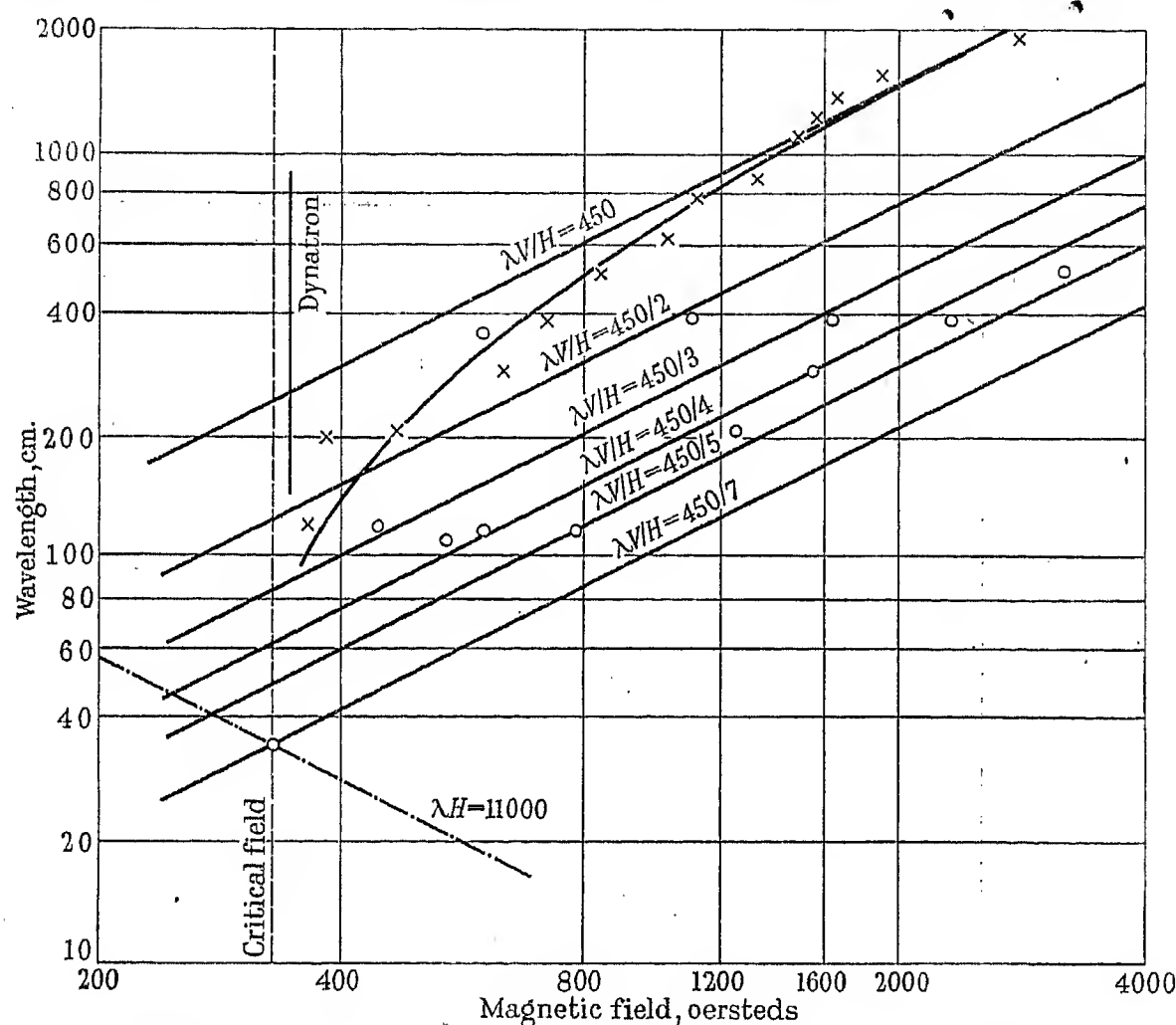


Fig. 3.—Wavelength of oscillations of 2-segment-anode magnetron.

$V_a = 600$. Anode diameter = 1 cm. (nominal).

x x Strong oscillations.
o o Weak oscillations.

value of $\lambda V/H$ for resonance oscillations, which is constant for wavelengths greater than 5 metres, decreases with wavelength down to the lower limit of the latter determined by the smallest circuit which can be connected to the valve. A further comprehensive series of tests was made on a 2-segment-anode magnetron in order to determine its behaviour at still shorter wavelengths with a special view to finding the relation, if any, between resonance and electronic oscillations. For this purpose a Lecher wire circuit was used as the external circuit and the conditions for oscillation were noted with various lengths of circuit at a series of anode voltages between 60 and 2 000.

The experimental results may conveniently be summarized as follows:—

(1) The value of λH was found to vary considerably, in general over a range 8 000 to 14 000, with a preponderance

than that field. At high anode voltage the electronic oscillations occurred usually at magnetic fields about 20 % in excess of the critical field.

A list of observations made with a 2-segment 1 cm. diameter anode valve, illustrating some of the points enumerated above, is given in Table 2. The results given in the Table have been so selected that with one or two exceptions the product of wavelength and magnetic field was very roughly equal to 11 000.

In all the above results the value of the observed magnetic field which corresponded to maximum amplitude of oscillation was subject to an error of about 10 %. The filament current was, in general, considerably below that for full emission, and showed a fairly pronounced optimum value for each oscillation.

Most of the oscillations recorded in Table 2 are such that the value of λH is so nearly 11 000 that they would

be classed as electronic oscillations. It will be noted, however, that the magnetic field at which they occurred was sometimes less and sometimes greater than the critical field calculated from the diameter (1 cm.) of the anode. A number of static characteristics of anode

Table 2

Anode volts V	Wave-length λ , cm.	Critical magnetic field [$H_c = \sqrt{180V}$]	Observed field H	λH	$\frac{\lambda V}{H}$
60	180	105	60	11 000	180
	67		82	5 500	49
120	136	145	95	13 000	170
	88		105	9 300	100
	63		170	10 700	44
180	64	180	160	10 200	72
	38		190	7 200	36
240	60	210	186	11 000	77
	39		270	10 500	35
300	65	230	210	14 000	93
	39		270	10 500	43
480	29	295	370	11 000	38
600	29	330	370	11 000	47
1 100	21	445	540	11 500	43
1 500	19.5	520	600	12 000	49
	15.5		700	11 000	33
1 800	14.5	570	780	11 500	34

current against magnetic field were taken and these showed that the magnetic field calculated from relation (4), viz. $H^2 = 180V$, always lay on the steep portion of that characteristic and was a reliable indication of the

critical field. Certain of the oscillations given in Table 2 occurred, therefore, at magnetic fields appreciably different from the critical value. In Fig. 4 the value of $\lambda V/H$ given in Table 2 is plotted against the ratio of the actual to critical magnetic fields. It will be seen that there is a continuous variation in the magnitude of $\lambda V/H$, and that when the actual field equals the critical field the value of $\lambda V/H$ is approximately 60 as noted in relation (5).

The tendency for electronic oscillations to be confined to a limited number of wavelengths is brought out in Table 3, in which the observed wavelengths recorded in Table 2 are given in the first column.

The Table also shows that the ratio of any two con-

Table 3

Observed wavelength, cm.	S	$15 \times 2^{S/2}$
15	0	15
21	1	21
29	2	30
39	3	42
62	4	60
88	5	85
136	6	120
180	7	170

secutive wavelengths was approximately equal to $\sqrt{2}$. The practical importance of the results emphasized in Table 3 is that electronic oscillations tend to occur at discrete wavelengths, and that no adjustment of magnetic field or anode voltage will enable a continuous adjustment of wavelength to be made over any considerable range. It should be pointed out that this discontinuity in wavelengths was obtained only for wavelengths so short that the external circuit was not resonant at its fundamental frequency. The series of wavelengths of oscillations given in Table 3 should not be confused with the so-called higher-order electronic oscillations reported by Groos⁵ and other workers. The product of wavelength and magnetic field for these oscillations in a

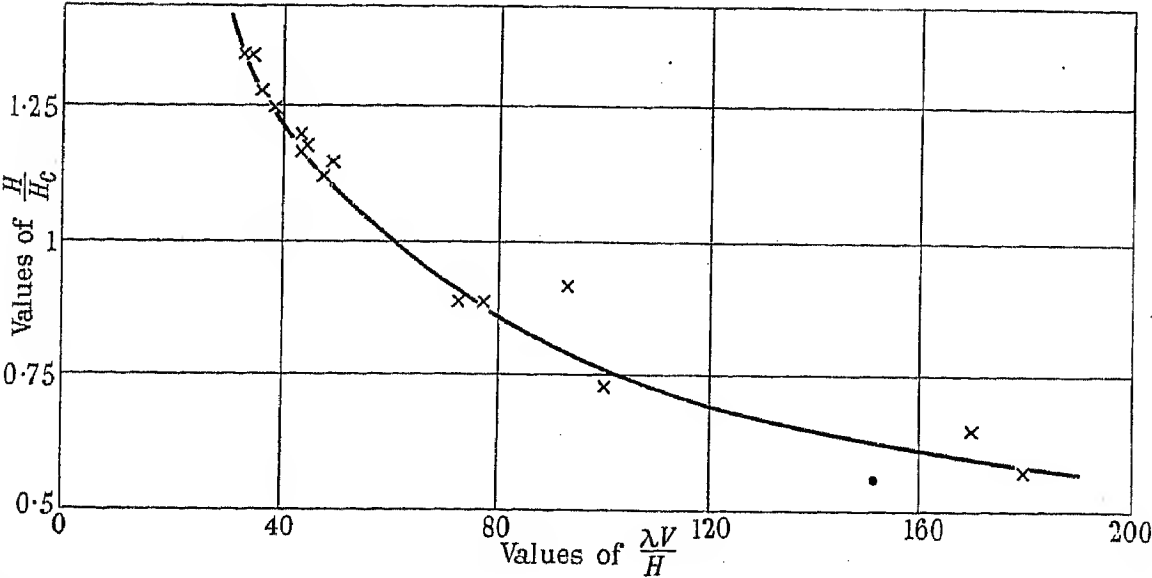


Fig. 4.—Ratio of actual H to critical H , plotted against $\lambda V/H$ for electronic oscillations. $\lambda H \simeq 11\,000$ for 2-segment-anode magnetron with anode voltages 60–1 800.

2-segment-anode magnetron has a series of discrete values greater than 11 000. The oscillations given in Table 2 were obtained for a wide range in anode voltages and magnetic fields but were all such that the product of wavelength and magnetic field intensity was approximately 11 000. The higher-order electronic oscillations, on the other hand, are such that that product has a series of values. These higher-order electronic oscillations were observed but they did not agree closely with the formulae given by Groos.

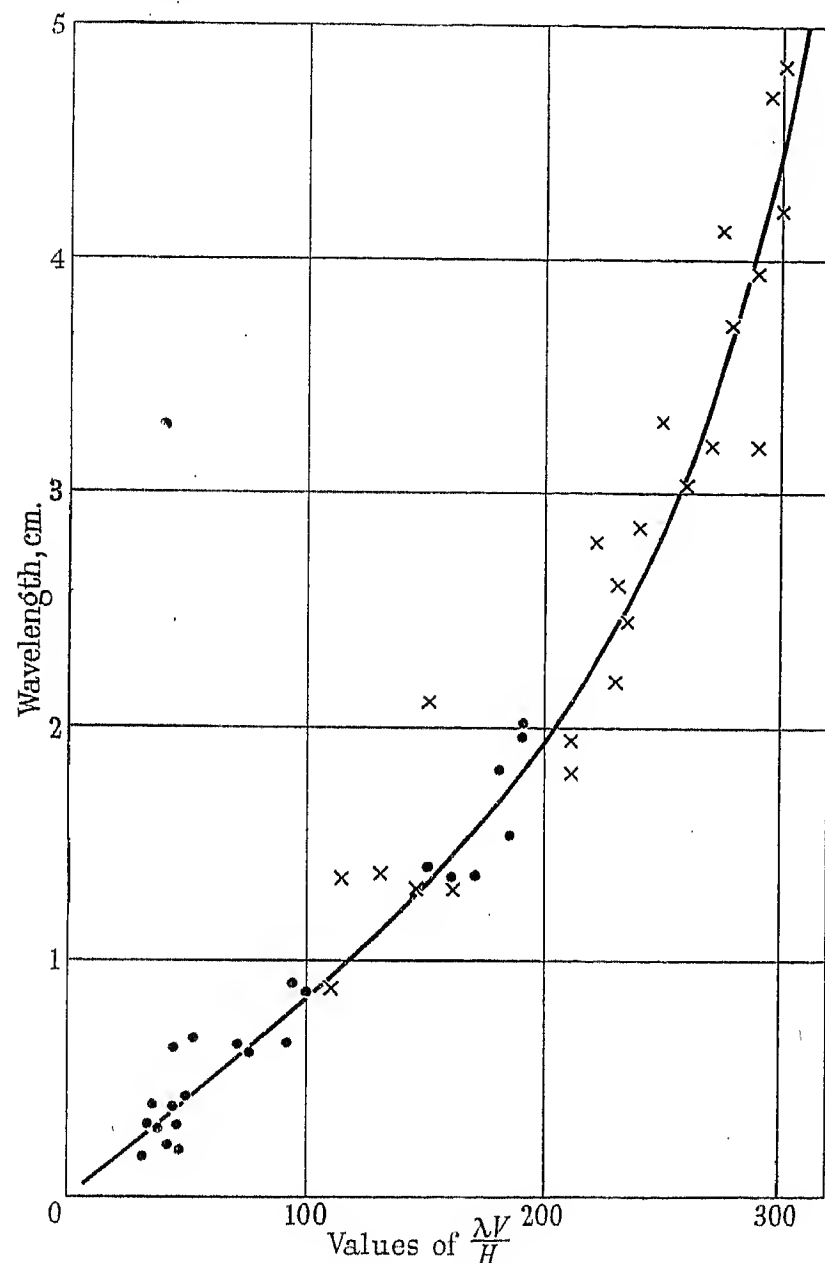


Fig. 5.—Wavelength plotted against $\lambda V/H$ for 2-segment-anode magnetron: resonance and electronic oscillations.

$V_a = 60-1\ 800$; λ in cm., V in volts, H in oersteds.
 × × Resonance oscillations.
 ● ● Electronic oscillations ($\lambda H \approx 11\ 000$).

Electronic oscillations of longer wavelength fall into the region in which resonance oscillations occur. This is shown in Fig. 5, in which the value of $\lambda V/H$ is plotted against λ for a large number of oscillations obtained with a 2-segment valve at a series of anode voltages varying from 60 to 2 000. The resonance oscillations are shown by crosses, while those oscillations for which $\lambda H = 11\ 000 \pm 3\ 000$ are shown by dots. It will be seen that both the sets of points lie on a smooth curve and that they overlap in wavelength. The dots represent oscillations which would be termed electronic, while the crosses correspond to resonance oscillations. For a 2-segment valve similar

in dimensions to that used in the above experiments Gill and Britton determined the magnitude of $\lambda V/H$ to be approximately 400 for resonance oscillations. As the value of $\lambda V/H$ in Fig. 5 decreases continuously with decrease in wavelength from about 400 to 30–40 for oscillations which obey the electronic law $\lambda H = 11\ 000$, there would appear from the experimental results to be no essential difference between these two types of oscillation.

(c) Four-Segment Magnetron

A number of measurements similar to those described above were made with a 4-segment-anode valve having the same nominal dimensions as the full-anode and 2-segment-anode valves used in the earlier experiments. As is common practice with multi-segment valves, alternate segments were connected together within the valve

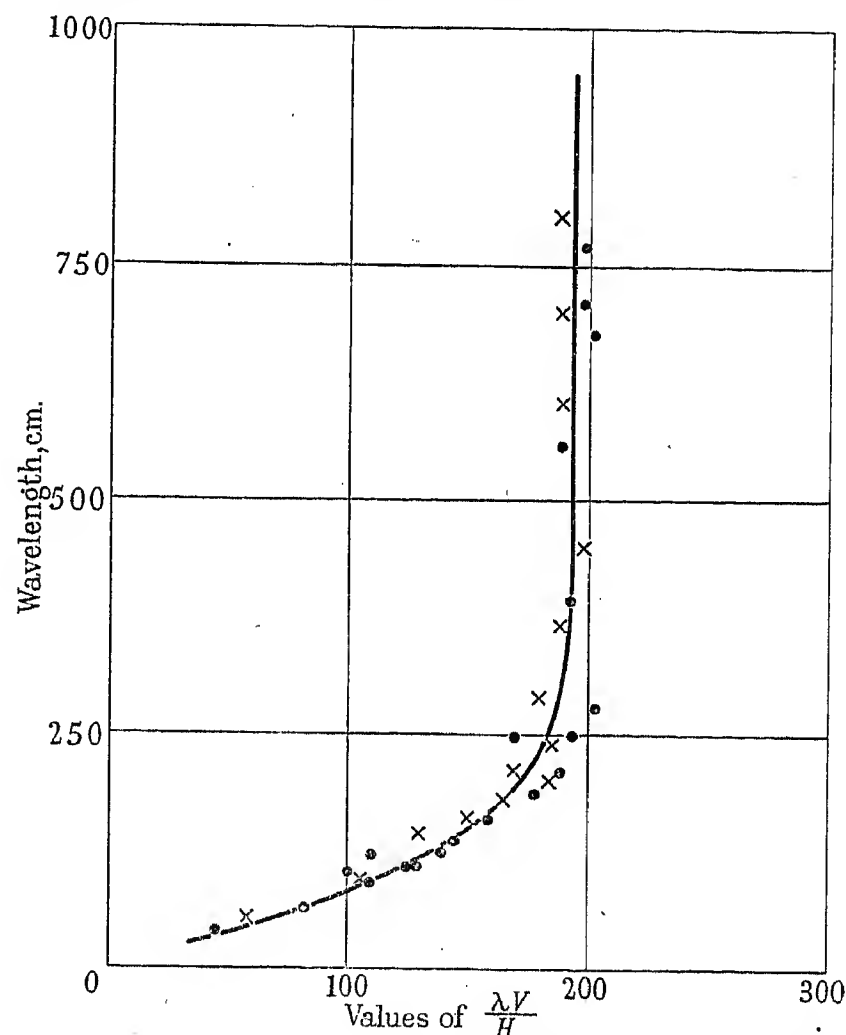


Fig. 6.—Wavelength plotted against $\lambda V/H$ for 4-segment-anode magnetron. λ in cm., V in volts, H in oersteds.

× × $V = 180$ volts.
 ● ● $V = 300$ volts.

envelope. With the 4-segment valve the tendency to produce dynatron oscillations was much less pronounced than with the 2-segment valve. This characteristic of the 4-segment valve allowed a fuller investigation of the conditions required for the production of short-wave resonance oscillations. This could not be done so easily with the 2-segment valve, in which dynatron and resonance oscillations of short wavelength occurred under closely similar conditions. A Lecher wire circuit was used in this case so that overtone resonances of the external circuit would allow of very short-wavelength oscillations being produced. The results obtained with the 4-segment

valve are given in Fig. 6. Considerable difficulty was experienced at the longer wavelengths owing to the variation of the optimum value of magnetic field for a given wavelength with the setting of filament current. An increase in filament current produced at least an equal percentage increase in the value of the optimum magnetic field. Since the minimum filament current for which oscillations could be maintained tended to increase with wavelength, this resulted in a distinct tendency for the observed value of $\lambda V/H$ to decrease with increase in wavelength above about 10 metres. The results given in Fig. 6 were obtained with the oscillation amplitude as small as possible. They are similar to those found for the

similar to those described above on a 2-segment valve, to see whether oscillations other than the normal dynatron or resonance types could be obtained. The results of these experiments are shown plotted in Fig. 7. It will be seen that although most of the points lie near the curve which coincides asymptotically with the straight line given by $\lambda V/H = 190$, a number of oscillating conditions were obtained for which the value of $\lambda V/H$ was approximately 400. This latter value is similar to that found in the case of the 2-segment valve and also, in fact, coincides with the maximum value of $\lambda V/H$ obtainable with the full-anode valve when correction is made for the difference in apparent diameters of the two anodes. The

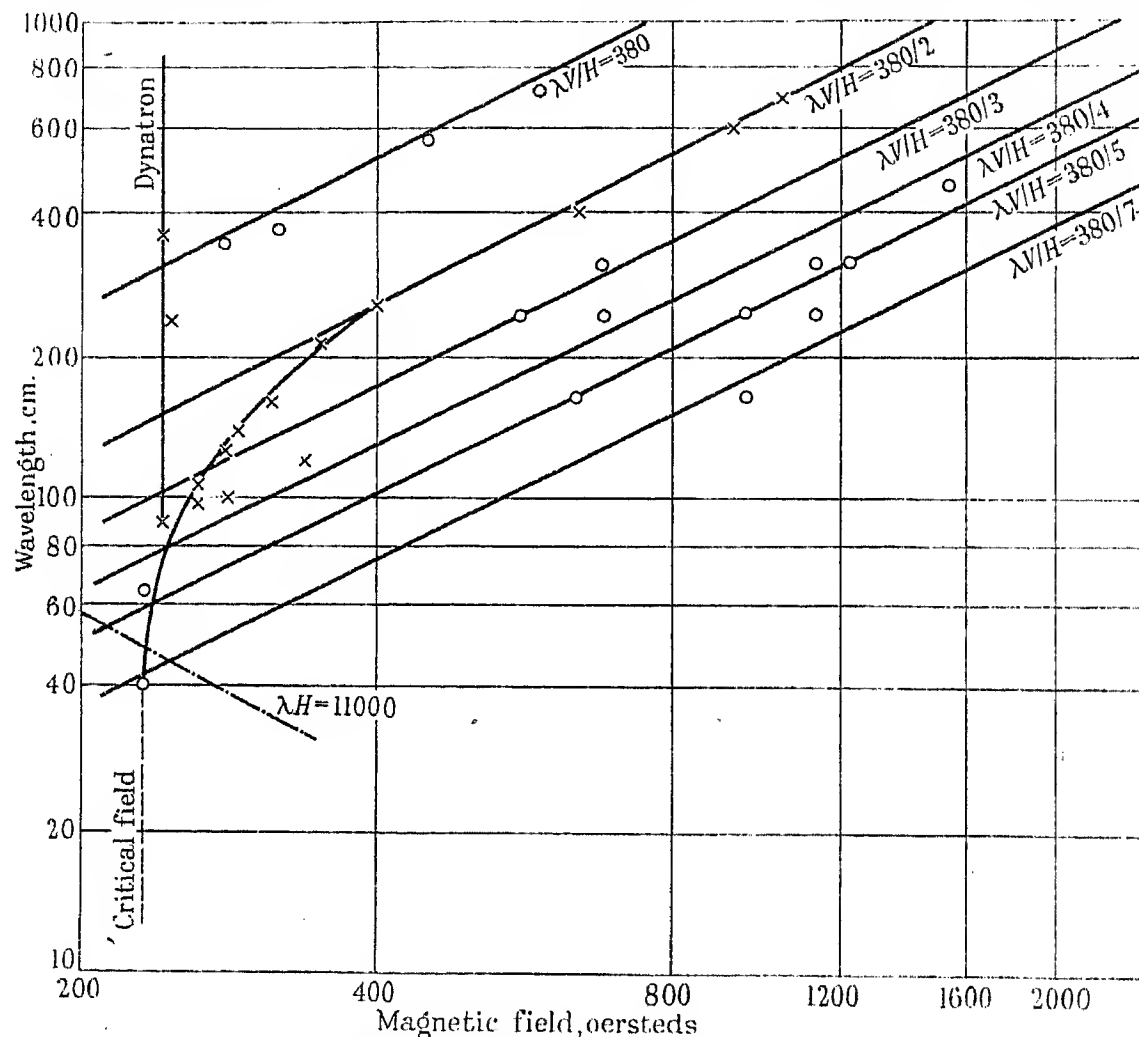


Fig. 7.—Wavelength of oscillations of 4-segment-anode magnetron.

$V_a = 300$ volts. Anode diameter 1 cm. (nominal).
 x x Strong oscillations.
 o o Weak oscillations.

2-segment valve, the value of $\lambda V/H$ decreasing gradually as the wavelength of the oscillations decreases. The maximum value of $\lambda V/H$ is about 200 instead of 400 as in the case of the 2-segment valve of similar dimensions, thus corroborating relation (3).

The shortest wavelengths plotted in Fig. 6 are of the electronic type, and the same continuity between resonance and electronic oscillations as was found with the 2-segment valve is apparent. The electronic region was not investigated in as much detail as with the 2-segment valve, but a general similarity of behaviour was evident. A number of cases occurred in which the value of λH was about 7 000 and one wavelength persisted over a range of voltages, although in not so pronounced a manner as with the 2-segment valve.

Experiments were also made on a 4-segment valve,

dots shown in Fig. 7 correspond to weak oscillations. It will be seen that they lie approximately on the lines given by $\lambda V/H = 380/n$. These values of $\lambda V/H$ are the same as those found for both 2- and single-segment valves of the same anode diameter. The results suggest, therefore, that both the 4- and 2-segment valves may act as single as well as multi-segment valves. This is not surprising when it is remembered that in the case of the full cylindrical-anode valve the external circuit appeared to have little or no effect on the wavelength of oscillation.

(d) Relation between Wavelength of Resonance Oscillation and Anode Current

The experimental results given above show that the factor $\lambda V/H$ is a constant for large magnetic fields and

decreases when for a given anode voltage the magnetic field and wavelengths are reduced. $\lambda V/H$ is a constant, therefore, over those parts of the anode-current/magnetic-field characteristic corresponding to small anode current, and the curved portions of the $\lambda V/H$ curves in Figs. 3 and 7 are confined to regions near the critical magnetic field for which the static anode current varies rapidly with change in magnetic field. It was considered that the variation in $\lambda V/H$ might be related directly to the static anode current. The static characteristic connecting the anode current i with the magnetic field H was measured for

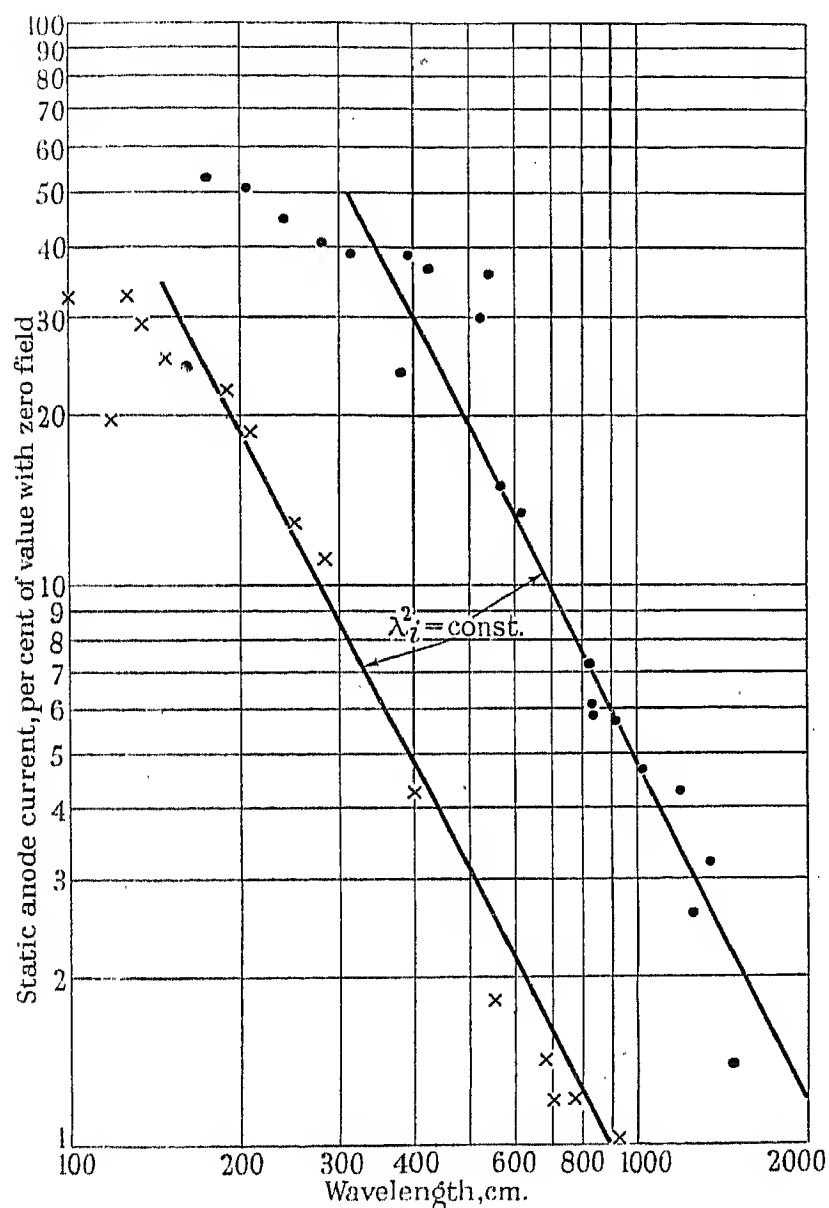


Fig. 8.—Static anode current plotted against wavelength for 2- and 4-segment-anode magnetrons.
 •• 2-segment. ×× 4-segment.

each experiment with a filament current sufficiently small to avoid oscillations. From the results obtained in this way it was possible to approximate to the static anode current appropriate to each wavelength of oscillation by determining the anode current corresponding to the magnetic field for maximum oscillation output. Typical results relating the wavelength to the static anode current are given on a logarithmic scale in Fig. 8. It will be noted that over a large range of wavelengths the experimental points for both 2- and 4-segment valves lie closely to the straight lines given by

$$\lambda^2 i = \text{constant} \quad (6)$$

The experimental results which do not agree with this relation correspond to points on the anode-current/magnetic-field characteristic where the anode current varies too rapidly with magnetic field intensity for the appropriate anode current for each magnetic field intensity to be accurately determinable. It is interesting to note that Gill¹⁰ obtained an exactly similar relation to equation (6) above, between the wavelength of electronic oscillations in a positive-grid triode and the grid current. This additional similarity between electronic oscillations in triodes and resonance oscillations in magnetrons strengthens the hypothesis that the two types of oscillation are essentially the same.

Linder¹¹ has recently published theoretical formulae, supported by experimental results, which differ considerably from equation (6). The experimental results obtained by the authors, however, did not agree with Linder's theoretical formulae nearly so closely as with the purely empirical relation given above.

(e) Effect of Tilt

Most workers on the magnetron are agreed that the angle between the magnetic lines of force and the electrode axis is of importance for optimum conditions of oscillation and is not in general zero.^{3,7} There is not the same agreement, however, as to the circumstances under which this tilt becomes advantageous or even essential. The experiments described above were conducted with angles of tilt ranging up to about 7°. The effect of tilt was not, in general, simple, and did not always repeat as between two valves nominally identical and working under the same conditions. The main effect of tilting the valve seemed to be a broadening of the range of magnetic field over which oscillation took place, possibly because the static anode-current/magnetic-field characteristic curve slopes less steeply when the valve axis makes a small angle with the direction of the magnetic lines of force. Thus an oscillation which required a setting of magnetic field current accurate to $\pm 5\%$ when the valve had zero tilt might be maintained with a range of magnetic field current of, say, $\pm 20\%$ when the valve had a small tilt.

(3) DISCUSSION OF RESULTS AND CONCLUSIONS

The experimental analysis of the behaviour of the magnetron as a short-wave oscillator is extremely complicated owing to the large number of factors controlling the amplitude of the oscillations and also their wavelength; the last-named, in some cases, is determined by a combination of the anode voltage, magnetic field, the angle of tilt which the valve axis makes with the direction of the magnetic field, and the external circuit. One valve may show a marked tendency to oscillate at some particular frequency determined, by, say, the length of lead from anode to seal, which has apparently little effect in a second nominally identical valve. Even if only one type of oscillation was produced by the magnetron a complete tabulation of its properties would be a formidable task as the optimum condition for each oscillation depends on the appropriate adjustment of all the factors controlling the oscillations, and they can never be determined with any great accuracy. As the magnetron can

be used to produce oscillations of two or three different types, sometimes simultaneously, an entirely satisfactory explanation of its behaviour determined empirically may be impossible.

The authors have not attempted to produce any hypothesis for the production of oscillations in the magnetron, but have confined themselves intentionally to an analysis of the results obtained in a large number of experiments. The following facts can be derived from this analysis.

(a) A full-anode magnetron can oscillate at a number of wavelengths with magnetic fields considerably greater than the critical value. The wavelength of these oscillations is almost independent of the external circuit, and the quantity $\lambda V/H$ may have any value given by $K, K/2, K/3 \dots K/n$. For a valve having an anode diameter of 1 cm., K will have a value of about 400. Sometimes oscillations at two distinct wavelengths occur for the same magnetic field. These oscillations must all be regarded as of the so-called resonance type.

(b) Weak oscillations similar to those for the full-anode valve are found in multi-segment magnetrons. Presumably the valve acts as a single-segment magnetron under these conditions.

(c) With multi-segment valves the resonance oscillations of largest amplitude are those for which $\lambda V/H$ is approximately $1/p$ times the maximum value of $\lambda V/H$ for a similar-dimensioned valve having a full anode, where p is the number of pairs of anode segments, e.g. for a 1 cm. diameter valve $\lambda V/H$ for maximum oscillation amplitude is 400 and 200 for 2- and 4-anode-segment valves, respectively.

(d) The value of $\lambda V/H$ for the main resonance oscillations on a multi-segment valve decreases from a constant value at the longer wavelengths to a considerably lower value at the shortest wavelengths possible with this type of oscillation.

(e) Electronic oscillations obeying the law $\lambda H = 11\,000$ may occur at magnetic field intensities both greater and less than the critical field.

(f) The value of $\lambda V/H$ for electronic oscillations increases with the wavelength of oscillation, becoming the same as that for resonance oscillation at a common wavelength.

(g) A continuous variation of wavelength of electronic oscillations with voltage does not occur.

(h) The product of the square of the wavelength of resonance oscillations and the static anode current is constant over a considerable range of wavelengths.

(j) The investigation shows that the electronic and resonance types of oscillation are essentially the same or that the electronic oscillation is only a special case of resonance oscillation.

The ability of the multi-segment magnetron to act simultaneously as a single-segment-anode valve and, therefore, to give rise to a series of wavelengths of oscillation for one setting of magnetic field may account for the experimental observation that the output from a magnetron, although periodic, is seldom in the form of a sine wave.

Gill and Britton¹ have put forward the hypothesis that the resonance oscillations found in multi-segment magnetrons are due to a precession of the electrons within the

valve set up by a combination of the static electric field between the filament and anode, the magnetic field, and the alternating potential between the anode segments due to the oscillations. The results described in the paper show that the same resonance oscillations occur both in single- and multi-segment anode valves having similar dimensions, but that by dividing the anode into a number of segments certain types of these resonance oscillations become predominant. As these resonance oscillations occur in a full-anode magnetron, it would appear that the precession of electrons occurs even in the absence of any alternating component of electric field between the segments of the magnetron, but that the effect becomes more pronounced on division of the anode into a number of separate segments.

Acknowledgments

The work described in this paper was carried out as part of the programme of the Radio Research Board, and thanks are due to the Department of Scientific and Industrial Research for granting permission for publication. The authors are also indebted to Mr. F. M. Colebrook, B.Sc., for advice on the method of presentation of the paper, and to Mr. C. G. Carter, B.Sc., for assistance with the measurements.

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A MAGNETRON OSCILLATOR WITH A COMPOUND FIELD WINDING*

By L. H. FORD, M.Sc., Associate Member.

(Paper first received 8th May, and in revised form 3rd November, 1939.)

SUMMARY

The possibility of using the anode current to excite additional coils on the electromagnet of a magnetron oscillator and thus control the magnetic field is discussed, and a description given of experiments made with such an arrangement. The direct connection, in which the anode current assists the main magnetizing current, is shown to be of doubtful value; but the differential connection, in which the anode current opposes the main magnetizing current, when used in conjunction with a series resistance in the anode circuit, is shown to possess advantages as a generator of resonance oscillations. The number of turns on the coils and the magnitude of the series resistance can be so adjusted that the quotient of anode voltage to field intensity is approximately constant over the range of oscillation, which improves the operational stability and is likely to improve the frequency stability. The danger of the anode becoming overheated if a sudden reduction of the load on the valve takes place is also removed.

(1) INTRODUCTION

The magnetic field of a magnetron oscillator is commonly provided either by a permanent magnet or by an electromagnet energized by a direct-current supply independent of those of the anode or filament of the valve. In the former case the desired oscillation conditions are obtained by adjusting the anode voltage, while in the latter case either the anode voltage or the magnetic field may be adjusted. The use of an electromagnet consequently increases the flexibility of an oscillator at the expense of a decreased overall efficiency, and is generally preferable if the oscillator is to be used at a number of frequencies, although adjustable "permanent" magnets are sometimes used.

When an electromagnet is used the possibility arises of using either the filament or anode currents of the valve to provide all or part of the magnetic field necessary for the operation of the oscillator. The work to be described was undertaken to determine whether the anode current can usefully be employed partially to control the magnetic field when the valve is oscillating in the resonance condition, with which wavelengths of 40 cm. and upwards are obtainable. For the resonance type of oscillation the condition $\lambda V/H = \text{a constant}^\dagger$ must be satisfied, so that the prospects of improving the performance by this means seemed worth while investigating.

Oscillations in an electromagnet type of magnetron are generally obtained by adjusting the magnetizing current

until the magnetic field reaches the required optimum, when the amplitudes of oscillation and anode current are maxima. The way in which the anode current supplied to the valve varies with the current in the coils of the electromagnet gives, therefore, a useful indication of the behaviour of the magnetron. A discussion of this, in the region of oscillation, is consequently given below for the cases of magnetrons with simple, direct compound, and differentially compound electromagnets, before going on to describe the experimental results obtained.

(2) RELATIONSHIP BETWEEN MAGNETIZING CURRENT AND ANODE CURRENT WITH RESONANCE OSCILLATIONS

(a) Simple Electromagnet

The relationship which exists between the exciting current of the electromagnet and the anode current of a magnetron valve oscillating in the resonance condition

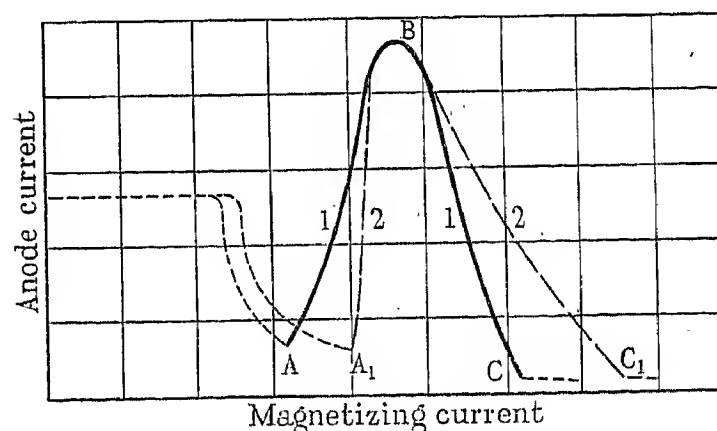


Fig. 1.—Relation between exciting current of simple electromagnet and anode current of magnetron.

is shown diagrammatically in Curve 1 of Fig. 1. As the magnetic field is increased the valve begins to oscillate weakly at a condition corresponding to the point A and the anode current commences to rise; as the field is further increased an optimum is reached at B, where the anode current and amplitude of oscillation are at maxima, after which a still further increase of the field causes the oscillation to weaken, with diminishing anode current until the point C is reached, when oscillation ceases. When the field is decreased from a value greater than C the cycle of events is similar in the reverse direction.

If a magnetron valve is used under conditions of maximum output a sudden decrease of load is liable to cause an increase in the oscillatory voltage with excessive anode heating; or secondary emission due to filament bombardment may cause the valve to become unstable, with disastrous results. A series resistance is, therefore,

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† Where λ = wavelength of oscillation, V = anode voltage, H = magnetic field.

frequently inserted in the anode circuit; this prevents the current from reaching a dangerous value by absorbing part of the supply voltage. Curve 2 of Fig. 1 shows the effect of such a resistance on the action of the valve, on the assumption that the supply voltage has been increased to bring the anode voltage to the same value as for Curve 1 when the optimum oscillation condition is established. The value to which the field current must be brought before oscillations begin is increased from A to A_1 , since the anode voltage with small anode currents is greater than before, but the curve rises more steeply to its maximum value, which again occurs at B. The decay of oscillations as the magnetizing current is further increased is delayed, owing to the rise in anode voltage as the anode current falls, until oscillations finally cease at C_1 .

(b) Direct compound electromagnet

When the anode current of the valve is passed through coils on the electromagnet in the direction which increases the field due to the current in the main magnetizing coils,*

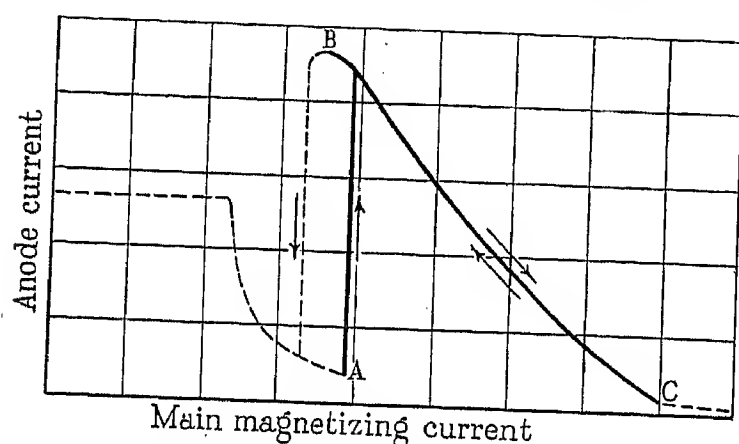


Fig. 2.—Relation between anode and main magnetizing currents of direct compound electromagnet.

the effect is similar to that of series resistance in the anode circuit. In the one case the anode current increases the value of H , and in the other it decreases the value of V , so that the effect on the quotient V/H is the same in both cases.

An interesting possibility occurs if the anode current is passed both through coils on the magnet and through a series resistance. As explained in the previous Section, the effect of the series resistance is to increase the value of main magnetizing current at which oscillation begins, and this will outweigh the tendency of the additional coils to increase the magnetic field, since immediately before oscillation the anode current is relatively small. Consequently, when oscillation begins the rapid rise in anode current may increase the magnetic field to a greater value than that suitable for maximum oscillation, which would then be attainable by making a reduction in the main field current. A decrease of the main field current below the value necessary to bring the anode current to its maximum value must then cause an abrupt cessation of oscillation, since any decrease in anode current produces a reduction in magnetic field which in itself further decreases the anode current. The connection between

anode and main magnetizing currents is shown diagrammatically in Fig. 2.

(c) Differential compound electromagnet

In addition to the possibility of using the anode current to energize field coils on the electromagnet and thus provide part of the required magnetic field, the anode current may be passed through the coils in the opposite direction, reducing the total magnetic field to a lower value than that obtained with the normal magnetizing winding only. Since a series resistance in the anode circuit causes the anode voltage to be a minimum when the current is a maximum, and differential connection of the field coils carrying the anode current will cause the total magnetic field to be a minimum when this current is a maximum (the main magnetizing current remaining unaltered), suitable proportioning of the series resistance and the number of turns on the field coils will cause the quotient V/H to remain constant over the whole range of anode current within which oscillation occurs. Resonance oscillations require a constant quotient of V/H , so that

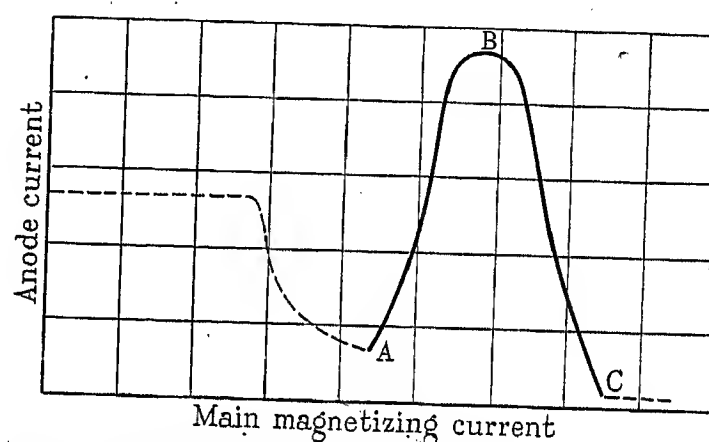


Fig. 3.—Relation between anode and main magnetizing currents of differential compound electromagnet.

this arrangement appears likely to have advantages in securing both stability of operation and greater constancy of frequency of the oscillations generated.

Since the effect on the behaviour of the valve of the magnetizing coils in the anode circuit tends to be the reverse of that of series resistance, the probable curve between anode current and main magnetizing current, shown diagrammatically in Fig. 3, will be not dissimilar from that for the simple electromagnet magnetron, with the values of main magnetizing current increased.

(3) EXPERIMENTAL RESULTS

Experiments were made on the possible arrangements of magnetic field system described above, using 4 valves, each having a 4-segment anode, to give resonance oscillations of 1 metre wavelength. The general arrangement of field and anode circuits was as shown in Fig. 4. The main field coils on the limbs of the magnet consisted of about 3 000 turns of No. 16 S.W.G. copper wire, and additional coils of 20 000 turns of No. 28 S.W.G., through which the anode current passed, were placed on the poles. The normal conditions of operation required a field current of 3 amperes when the anode voltage and current were about 2 000 volts and 150 milliamperes respectively. Consequently, with 5 000 ohms in series with the anode

* The use of this connection of the magnetizing winding to improve the modulation of the magnetron has been previously described—Patent No. 421652, Messrs. Marconi, Ltd., and A. W. Ladner, 1934.

and the current flowing in the additional coils in opposition to the main current, it was necessary to increase the supply voltage to about 2 700 volts and the main field current to 4 amperes. The percentage reduction in magnetic field due to the anode current coils was, therefore, approximately equal to the percentage reduction in anode voltage due to the drop in the series resistance. The oscillatory circuit consisted of a Lecher wire system bridged at a point about 60 cm. from the anode seals of the valve. With this circuit oscillations of about 40 cm. and 3.5 metres, as well as 1 metre, could be obtained by suitable adjustment of magnetic field. The load used was a de-capped 100-watt carbon-filament lamp which could be applied at any point on the circuit.

Experiments were made on each valve, at 1 metre wavelength, with the field system used first as a simple electromagnet, the coils AA being disconnected, and then

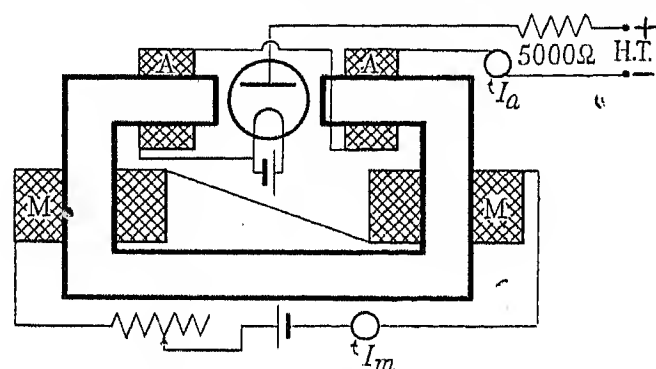


Fig. 4.—Compound magnetron.

with the anode current flowing through these coils both in the direction to assist and to oppose the main magnetizing current in the coils MM.

(a) Simple electromagnet

The behaviour of the oscillator was quite normal, as outlined in Section 2(a), Fig. 1, curve 2. Oscillation commenced weakly, built up to a rather blunt maximum, and decreased relatively slowly as the magnetizing current was increased through the range over which oscillation occurred. The magnetizing current, H.T. supply, anode current and power output in the lamp load were noted with the magnetic field adjusted for maximum output. It was found generally that removing the load left the anode current unchanged, or even slightly increased, with a marked increase in anode heating. This effect would occasionally occur, apparently owing to some chance variation, without any actual movement of the lamp serving as a load; that is, the lamp would go black and the valve anode brighten without any considerable change in anode current such as would occur if oscillation ceased. Sometimes, however, oscillation ceased completely with removal of the load, and in such cases could only be started again by readjusting the magnetic field. The stability of operation appeared to be quite good, but no run of greater than half-hour duration was attempted, since it was inadvisable to leave the set unattended owing to the danger of increased anode heating with a chance decrease in load.

(b) Direct compound electromagnet

The previous experiments were repeated with the anode current flowing through the additional coils in the

direction to assist the main field. It was found that oscillations could be obtained more readily if the main magnetizing current were reduced from too high a value than if it were increased from too low a value. In the latter case the behaviour was as outlined in Section 2(b), and a decrease of main magnetizing current from the value at which oscillation commenced caused an increase in output. The output increased as the magnetizing current was reduced, and then oscillation ceased abruptly at about the same output as previously obtained under similar conditions with the simple electromagnet, when the efficiency and the value of $\lambda V/H$ were also substantially the same as before. The effect of removing the load was almost invariably to cause oscillations to cease, which made it difficult to adjust the load to the optimum position on the circuit. The stability, as judged over relatively short periods, was good, provided that the field was adjusted to above the optimum value so that the output was appreciably below the maximum. Such adjustment did not involve any considerable loss in valve efficiency. When oscillating under these conditions a small decrease in anode current will decrease the magnetic field, and thereby tend to increase the anode current, and vice versa. Thus good stability is to be expected under these conditions. There was a tendency with some valves for a second peak of output to occur in this region with about two-thirds of the maximum output. It was not very pronounced, and when it occurred the combined magnetic field due to the coils A and M was almost the same for the two maxima.

(c) Differential compound electromagnet

The previous experiments were repeated with the anode current flowing through the additional coils in the direction opposing the main field. Oscillation started rather abruptly at almost maximum output when the main magnetizing current was increased to the necessary value, and disappeared almost equally abruptly when the current was further increased to a value about 10 per cent greater than that at which oscillation had begun. When the main magnetizing current was on the low side of the optimum value there was a marked tendency to instability of anode current, both when oscillations were just starting and just on the point of ceasing. This tendency was much less marked when the main magnetizing current was greater than the optimum value.

When the load was removed the anode current dropped to about one-half of its previous value, rising again to its full value when the load was replaced. This effect occurred with each of the four valves used in the experiments and is of the greatest value. The output and efficiency seemed somewhat greater than were obtained when using a simple electromagnet, but this may have been due to the ease with which the load could be adjusted to its optimum position in the circuit, and to the tendency of the magnetron to adjust itself automatically to maximum output with this connection. The stability was very good. For the first hour or so after switching on an occasional adjustment of the resistance in the main magnetizing circuit was necessary to compensate for the temperature rise in the field coils and maintain the current constant, but when thermal equilibrium was

reached the oscillator ran completely unattended for periods of an hour or more without any noticeable alteration in output. Experiments were not extended over a longer period than two hours, but there seems no reason to anticipate that, given constancy of supply voltages, the oscillator would not continue to run indefinitely.

The results obtained on one of the four valves used in the experiments described above are given in the Table. It was a 4-segment valve with an anode diameter of 1 cm. and length of 2.5 cm.; the supply voltage was 2 500, and 5 000 ohms were inserted in series with the anode. The wavelength was 1 metre.

(4) DISCUSSION OF RESULTS, AND CONCLUSIONS

A magnetron oscillator with a compound field winding, connected so that the anode current increases the mag-

whole range of oscillation, and output remains almost constant at its maximum value over this range. Removal of the load usually leads to a drop in anode current without interruption of the oscillations; there is thus complete protection against the danger of the valve overheating in these circumstances while the full oscillations are resumed when the load is restored.

There remain to be considered two disadvantages not directly connected with the oscillator as such. The resistance of the compound field coils must be appreciable (in the magnet system described it was 1 000 ohms), and consequently there is a difference of potential between the negative H.T. supply and the filament of the valve. There is also an increased power consumption, both in the anode circuit and main field circuit, which was nearly 200 watts in the experiments described. The drop in overall efficiency thus caused is not, however, of very

Table

Connection	Magnetic field, oersteds			Anode		Output, watts	Efficiency, %	$\frac{\lambda}{V}$ $\frac{H}{H}$
	Main coils	Anode coils	Total	Current (mA)	Volts			
Simple	1 000	0	1 000	150	1 750	70	27	175
Direct compound	680	320	1 000	120	1 900	60	26	190
Differential compound ..	1 270	380	890	140	1 800	70	28	200

NOTE.—The four valves used showed considerable differences in efficiency, ranging from 25 % to 60 %, due presumably to differences in construction.

netic field, possesses the disadvantages that its maximum output occurs under conditions such that either a slight decrease in magnetic field or removal of the load will, in most cases, bring about a cessation of oscillation. This tendency to stop oscillating with removal of the load is at the same time an advantage, since the valve is thus completely protected against the danger of overheating which frequently occurs with a simple magnetron under these circumstances. Thus a direct compound connection may be of use as a safety device serving substantially the same purpose as a series resistance in the anode circuit, without requiring so great an increase in anode supply voltage and with a greater overall efficiency.

A differential connection, in which the anode current opposes the main current, used in conjunction with a series resistance in the anode circuit possesses important advantages. If the number of turns on the coils and the magnitude of the series resistance are so chosen that a change in anode current produces an equal proportional change in both magnetic field and anode voltage, the quotient V/H remains substantially constant over the

great importance since the efficiency of the valve itself is not affected. The possible anode dissipation for a given valve is fixed; the valve efficiency determines the maximum output available, and is of the utmost importance. An additional loss, even of a few hundred watts, in the other parts of the magnetron equipment is not serious if corresponding advantages are obtained.

It may safely be said, therefore, that a magnetron having a differential compound electromagnet of the type described has advantages over the simple magnetron which considerably outweigh the disadvantages, and such a magnetron should be of use as a generator of resonance oscillations of short wavelength.

Acknowledgments

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THE IMPEDANCE OF THE MAGNETRON IN DIFFERENT REGIONS OF THE FREQUENCY SPECTRUM*

By A. F. HARVEY, B.Sc.(Eng.), Graduate.

(Paper first received 17th July, and in revised form 20th October, 1939.)

SUMMARY

A description is given of a series of measurements on the impedance of the magnetron and its relation to the operating conditions in different regions of the frequency spectrum. The object of the experiments was to determine the direct properties of the valve alone, in order to understand and explain the mechanism of operation of the magnetron. This has not been completely possible, and it appears that a full explanation is difficult unless existing theories of electron motion in the magnetron, especially under dynamic conditions, are much extended.

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- (2) Impedance in the Dynatron Regime.
- (3) Impedance in the Resonance Regime.
 - (a) Method of measurement.
 - (b) Wavelength and anode voltage.
 - (c) Magnetic field and voltage amplitude.
 - (d) Filament emission and angle of tilt.
 - (e) Reactance and phase angle.
 - (f) Generation of oscillations.
- (4) Impedance in the Electronic Regime.
 - (a) Filament emission and angle of tilt.
 - (b) Wavelength and magnetic field.
 - (c) Additional filament heating.
- (5) Conclusions.
- (6) Acknowledgments.
- (7) References.

(1) INTRODUCTION

The static characteristic of the split-anode magnetron is such that the valve behaves as a negative resistance to potential differences between the anode segments, when these are at a mean potential V , and this property persists in a range of H (magnetic field strength) from about the cut-off† value up to indefinitely strong fields. The negative resistance in this region of so-called dynatron

oscillation is sensibly independent of the wavelength provided this is long enough, and it persists down to wavelengths of the order 1 m. These oscillations, while giving high efficiency, result in only medium power outputs at comparatively long wavelengths.

The magnetron also has negative-resistance properties which are different from those mentioned above, and these are distinguished by the fact that they are only partly dependent on external conditions. It exhibits these properties from wavelengths of the order of 25 cm. up to indefinitely long wavelengths, and this regime is referred to as that of resonance oscillations. Here the magnetron is capable of giving with high efficiency the largest obtainable power outputs at ultra-short wavelengths.

In addition, the magnetron has negative-resistance properties at wavelengths which are such that the periodic time is closely related to the electron transit time. The valve properties in this regime, usually known as that of electronic oscillations, are practically independent of external conditions and relate to wavelengths usually less than 25 cm. Although the efficiency and power output are low, these oscillations include the shortest continuous waves that can be generated.

Most of the experiments described in this paper were made on a Marconi-Osram CW10 magnetron. The anode had a length of 2 cm., a diameter of 1 cm., and the segment gaps were about 2 mm. wide: the valve was rated for a dissipation of 50 watts with a maximum anode voltage of 1 200 volts and a maximum filament emission of 80 mA. Since the anode was in two segments the valve formed a symmetrical impedance; and the experimental results, unless otherwise stated, refer to voltage amplitudes and impedances for the complete valve, i.e. from one anode segment to the other.

(2) IMPEDANCE IN THE DYNATRON REGIME

The impedance (which is resistive) and properties of the magnetron in the dynatron regime and their relation to the static characteristics have been determined by the author,¹ whose measurements at short wavelengths have shown that until the wavelength falls below about 100 m. the resistance is constant, and after that it rises. This result is not unlike that given by normal dynatron and regenerative valve oscillators, and is a consequence of the electron transit time becoming an appreciable fraction of the cycle. Determinations of the resistance for very high values of magnetic field give results shown by the lower dotted line in Fig. 1. Up to a limiting value any increase of amplitude results in a decrease of resistance, and for

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† If e and m are respectively the charge and mass of the travelling particles and c is the velocity of light *in vacuo*, then for cylindrical electrodes the cut-off value H_c of magnetic field is given by

$$V = \frac{eH_c^2 a^2}{8mc^2} \left(1 - \frac{b^2}{a^2}\right)^2$$

which becomes $H_c^2/181$ in the case of electrons and when the anode radius a is 5 mm. and the cathode radius b is 0.065 mm.

small amplitudes the resistance is negative (and of very low value) close to the cut-off field. There does not appear to be a complete explanation for the existence of these properties, but it is probably due in some measure to the distortion of the electrostatic field by the potential difference between the segments, as has been suggested by E. W. B. Gill and K. G. Britton² and by H. Zuhrt.³

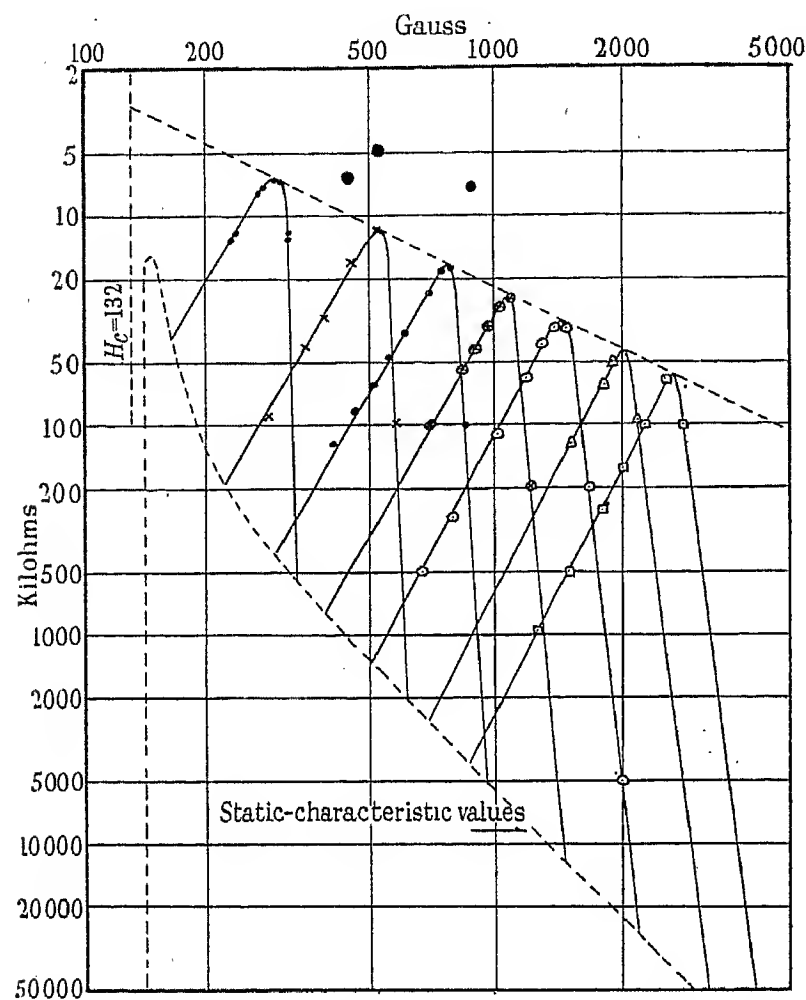


Fig. 1.—Variation of negative resistance with field strength at various different wavelengths.

Anode voltage, 100 volts.
Filament emission, 10 mA.
Amplitude, 29 volts (r.m.s.).
Wavelength 9.27 m. —●—●—●—
Wavelength 14.7 m. —x—x—x—
Wavelength 23.2 m. —●—●—●—
Wavelength 33.1 m. —⊕—⊕—
Wavelength 43.3 m. —○—○—
Wavelength 51.8 m. —△—△—
Wavelength 61.8 m. —△—△—
Wavelength 80.3 m. —□—□—

Since it will be useful later, it is instructive to consider, under static conditions, the radius of the electron cloud when $H \gg H_c$. If the cloud radius is r and the emission is assumed small, so that

$$\frac{V_r}{V} = \frac{\log r/b}{\log a/b}$$

then

$$\frac{r}{a} = \frac{H_c}{H} \cdot \frac{[1 - (b^2/a^2)]}{[1 - (b^2/r^2)]} \sqrt{\frac{\log r/b}{\log a/b}}$$

and for the valve used we have the values shown in Table 1, the last line giving for reference the measured anode current when both segments were at 100 volts with a filament emission of 10 mA. Thus at the higher field values considered in Fig. 1 the electron orbits are not far removed from the cathode.

It can be shown that with a finite emission the radius of the cloud is less and that if the space charge is sufficient to cause the field at the cathode to become zero then the cloud radius tends to one-half the above values. The conditions obtaining at cut-off, and the effect of tilt, have been examined by the author⁴ and it is expected that tilt (a) tends to reduce space charge by causing electrons to move longitudinally and finally leave the inter-electrode space, (b) inclines the axis of the cylindrical cloud and brings it nearer the anode to an extent depending on the angle of tilt and the length of the electrodes.

(3) IMPEDANCE IN THE RESONANCE REGIME

(a) Method of Measurement

This was carried out by connecting the anode segments to an external impedance consisting of a symmetrical double-rotor condenser (capacitance of each half variable between 30 and 200 $\mu\mu\text{F}$) and a coil (inductance between 0.9 and 18 μH) the centre point of which was kept at a steady potential. The dynamic resistance of this circuit, when connected to the valve with its filament cold, was determined as a function of wavelength. This was made by the distuning method or by connecting metallized resistors in parallel with the coil (and as close as possible to the valve terminals), or by inserting small series resistances (of eureka, No. 40 S.W.G.) in the lead connecting the two halves of the condenser. Suitable corrections were made for the inevitable distributed inductances and capacitances of the circuit, and the agreement of the three methods was then very good. The voltage amplitude was measured by a pair of small diodes which rectified the radio-frequency voltage, the resulting steady voltage across the load condenser being read by a high-resistance voltmeter. This instrument, which read sensibly peak voltage, was calibrated on a sinusoidal 50-cycle supply and the readings were assumed valid at the wavelengths employed. The voltmeter was connected across the valve terminals, and it will be noted that the damping resistance (about 5 M Ω) and input capacitance (about 1.8 $\mu\mu\text{F}$)

Table 1

H/H_c	1.0	1.8	4.0	7.0	12.8	27.2	36.3	58.8	∞
a/r	1	2	5	10	20	50	60	70	77
r/b	77	38.5	15.4	7.7	3.85	1.54	1.28	1.10	1.00
$I_a(\mu\text{A})$	10^4	25	5.0	1.1	0.1	0.003	—	—	—

were distributed equally across the two halves of the coil.

Much care was devoted to a choice of a suitable method of measuring the absolute valve resistance. Since the magnetron in this regime is equivalent to a complex non-linear impedance, the distuning method (capacitance or frequency variation) or methods similar to that due to P. W. Willans could not be employed. Finally, two methods were used according as the valve resistance was less than or greater than the rejector resistance of the external circuit. In the first, the valve and circuit together acted as a generator whose output voltage at various wavelengths was maintained at any assigned and constant value by placing an appropriate resistor in parallel with the core; and since the circuit has already been calibrated its rejector resistance is known at any wavelength when shunted by the known resistor. As the circuit power-factor was not large the fluctuations of anode potential are very nearly simple harmonic, and thus the fundamental component of negative resistance of the magnetron at any wavelength and amplitude is equal to the known rejector resistance. In the second method a voltage of the desired magnitude was induced from a separate electrostatically screened generator, self-oscillation of the magnetron being prevented by inserting sufficient resistance in the circuit. Then the filament of the magnetron was lit and the voltage amplitude brought back to its initial value by placing a suitable resistor in parallel with the coil, the circuit being retuned by slight adjustment of the condenser. The resistance necessary to do this is equal to the negative parallel resistance of the magnetron.

To reduce the uncertainties of measurement and the confusion which arises due to the different regimes in the magnetron associated with very short wavelengths, most measurements were made at comparatively long wavelengths. This necessitated the use of very strong magnetic fields, and values up to 3 500 gauss were provided by an iron-cored air-gap electromagnet of conventional form but of design appropriate to such intense fields.

(b) Wavelength and Anode Voltage

The negative resistance in the resonance regime is shown in Fig. 2 as a function of wavelength for three values of H . The value of E (r.m.s. voltage amplitude) chosen was such that the potential fluctuations of each anode were about $V/10$. It will be seen that the value of $-R$ (negative resistance) increases with λ (wavelength) in a comparatively gradual manner so long as λ is greater than a certain value depending on H , and that when λ is less than this value $-R$ increases much more rapidly; in either case $-R$ tends to the value given by the static characteristics, this being too high to be shown on the diagram. The minimum values of $-R$ lie on a line of unit slope (shown dotted), but it will be observed that for any given condition the value of λ is not critical and the magnetron would function well as a generator over a considerable range of wavelength if connected to a circuit of sufficiently high rejector resistance.

The existence of a sharply defined minimum wavelength is indicated from the theoretical analysis of the electron paths,⁵ while some light on the mechanism of these oscillations has been given by E. W. B. Gill and

K. G. Britton² and J. S. McPetrie.⁶ It is generally accepted that resonance oscillations are found only when λ (in cm.), V , and H have values given by $\lambda V/H = K$, where K is a constant depending on the diameter and number of segments of the anode, but the results given

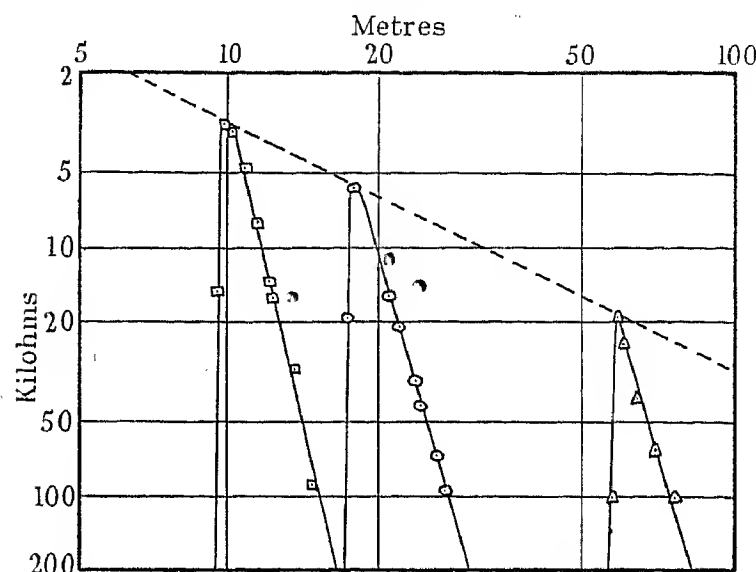


Fig. 2.—Variation of negative resistance with wavelength.

Anode voltage, 100 volts. Filament emission, 10 mA. Amplitude, 13.6 volts (r.m.s.).

Field strength 320 gauss —□—□—
Field strength 560 gauss —○—○—
Field strength 1 790 gauss —△—△—

show that negative resistance occurs over a considerable range of K . It will be convenient to use K as defined in discussing the experimental results, and thus for the conditions of Fig. 2 negative resistance occurs when K lies between 160 and 800. Measurements on the positions of minimum negative resistance give $K = 266$ when

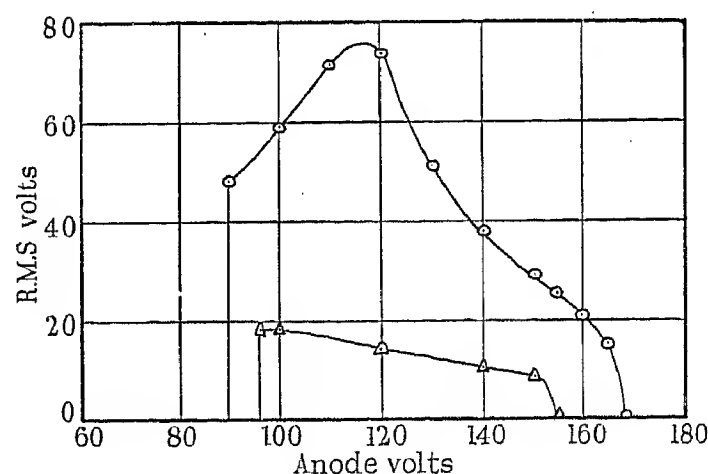


Fig. 3.—Variation of voltage amplitude with anode voltage.

Field strength, 2 215 gauss. Filament emission, 10 mA. Wavelength, 61.8 m
Negative resistance 115 kΩ —○—○—
Negative resistance 24.8 kΩ —△—△—

$E/V = 0.45$, $K = 325$ when $E/V = 0.136$ (as in Fig. 2), and $K = 405$ when $E/V = 0.026$.

The above curves were repeated for other anode voltages between 50 and 200 volts, and the values of $-R$ obtained were almost identical with those given above provided E/V was kept the same and H was altered with V so that K remained the same. Similar curves can be obtained when V is varied (instead of λ), but it is useful in this case to consider a fixed resistance and examine the changes in amplitude. Results for two values of $-R$ are given in Fig. 3.

(c) Magnetic Field and Voltage Amplitude

These "resonance" curves can also be derived when H is varied as in Fig. 1 for seven different wavelengths, from which it will be seen that the minimum value of $-R$ is proportional to λ as indicated by the upper dotted line. For a given value of λ there is only a restricted range of H in which the valve exhibits marked negative resistance; nevertheless, it is likely that the proportionate increase of $-R$ is not attributable to the increase of λ *per se* but to the effect of going further along the curved foot of the cut-off curve with the subsequent contraction of the electron cloud. As this value of H is proportional to V , while H_c varies as \sqrt{V} , the operating point moves along the curved foot as V is made larger.

Since negative resistance is not found for $H < H_c$ the Figure shows that for any value of V there is a minimum wavelength. The positions of minimum resistance are found to be given by $K = \lambda V / H = 300$, and as $H_c = \sqrt{(181 V)}$ the corresponding minimum wavelengths are given by $\lambda H_c = 54\,000$. Thus the minimum wavelength decreases as H_c (and hence V) increases. It will be seen later that a similar relation obtains for the wavelength of the electronic oscillations, but the value of the constant is then about 11 000. Provided sufficient field strength is available there appears to be no maximum wavelength to the resonance regime, and negative resistance (but of a very high value) would be found at indefinitely long (but not infinite) wavelengths. Accordingly the fact that self-oscillation is not encountered at long wavelengths is not due to any restriction by the properties of the magnetron; but is due to the lack of adequate circuits and the difficulty of providing the necessary intense fields.

Measurements show that the result of repeating the curves of Fig. 1 with other amplitudes is that $-R$ tends to increase with E , and since the valve impedance is given by the vector sum of the parallel impedances of the dynatron and resonance regimes the importance of carrying out these measurements at sufficiently long wavelengths to avoid confusion will be realized.

The curves in Fig. 4(a) show the relation between the fundamental component of negative resistance and the voltage amplitude, for three fields ranging from 11.3 to 16.8 H_c . It will be seen that the negative resistance is proportional to the amplitude so long as this is greater than a lower limit (which increases with field strength), and it should be understood that the almost vertical rise in negative resistance is a real effect. Since the relations result in straight lines directed to the origin it is evident that the fundamental component of anode current is constant whatever the voltage between the segments. It has recently been shown theoretically by G. Hara⁷ that in this regime the magnetron tends to have constant-current properties.

On the other hand, the mean anode current, as in Fig. 4(b), increases with voltage amplitude in a linear manner, and it should be noticed that it may be much less than the fundamental component; thus when $H = 1\,950$ the latter is always 0.61 mA (r.m.s.), whereas the input current can have any value (within limits) greater than 0.13 mA. A wave-form consistent with these results is difficult to conceive, and it is likely that the fluctuating component of anode current is not caused by the conduction effects familiar in normal valves. It is

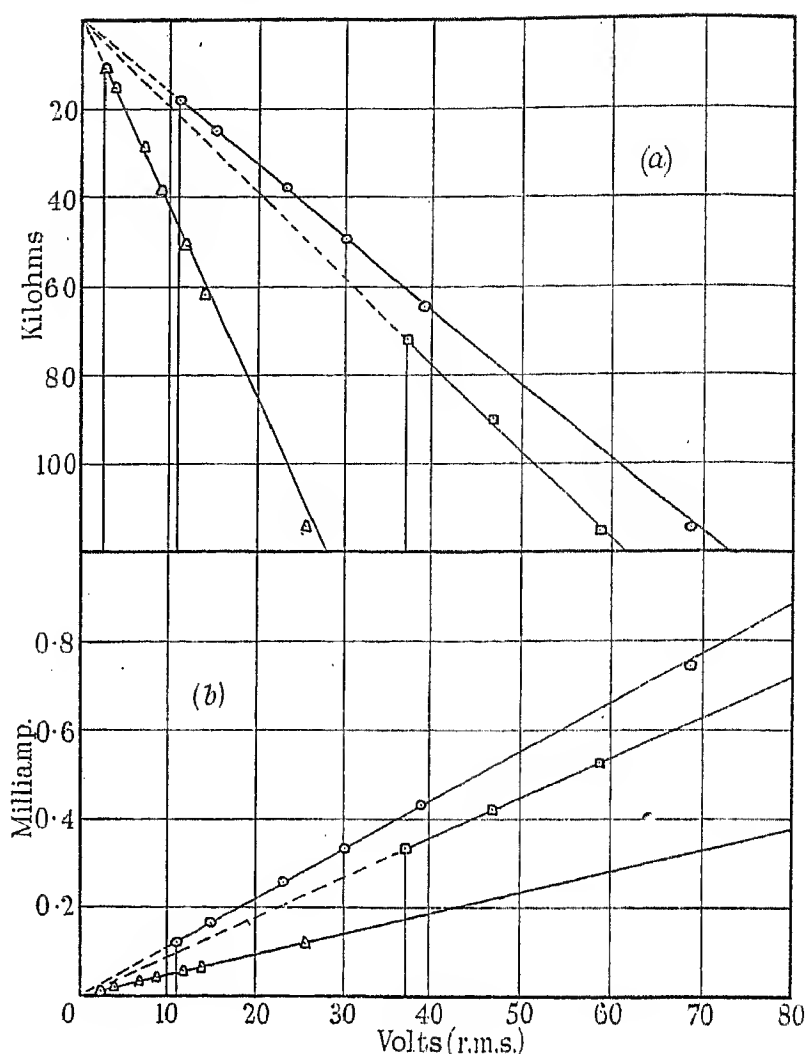


Fig. 4

(a) Variation of negative resistance with voltage amplitude.
(b) Variation of input current (d.c.) with voltage amplitude.
Anode voltage, 100 volts. Field 1 525 gauss —△—△—
Filament emission, 10 mA. Field 1 950 gauss —○—○—
Wavelength, 61.8 m. Field 2 260 gauss —□—□—

observed that the valve resistance does not decrease indefinitely as the amplitude and field strength are reduced, but tends to a minimum. Fig. 5 shows that the relation between these minimum resistances and wavelength is linear and results in a value of K of 282.

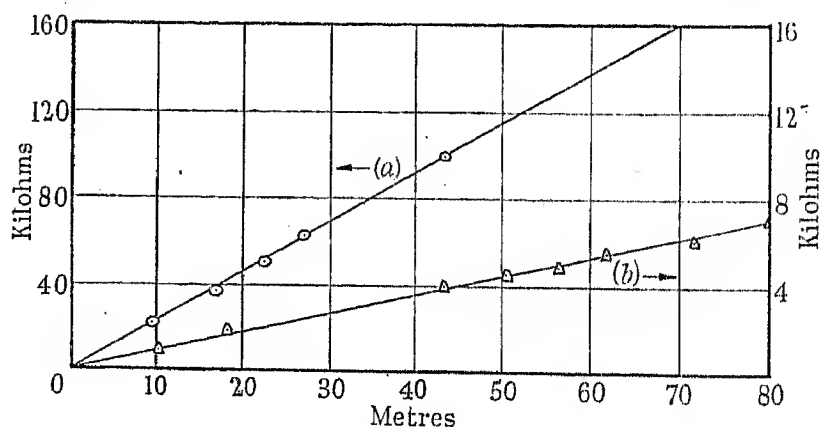


Fig. 5

(a) Variation of optimum load resistance with wavelength.
Anode voltage, 200 volts.
Field strength, optimum.
Filament emission, 10 mA.
(b) Variation of minimum negative resistance with wavelength.
Anode voltage, 100 volts.
Field strength, optimum.
Filament emission, 10 mA.

(d) Filament Emission and Angle of Tilt

The previous results have been obtained with I_e (total filament emission) large enough to make the valve resistance sensibly independent of it. Fig. 6(a) shows how $-R$

decreases, as I_e increases, to a blunt minimum and then slowly increases for large values of I_e . It is also found that λ varies with I_e , and by measuring the minimum value of λ (which is well defined, as Fig. 2 shows) for given conditions the results of Fig. 6(b) were obtained. It will be seen that the wavelength for a given amplitude and field increases as I_e decreases, which is the opposite to what would be expected if this "resonant" wavelength were directly related to the electron transit-time.

Fig. 7(a) shows how I_a (mean anode current) and the power E^2/R (the input to a load resistance R) vary with

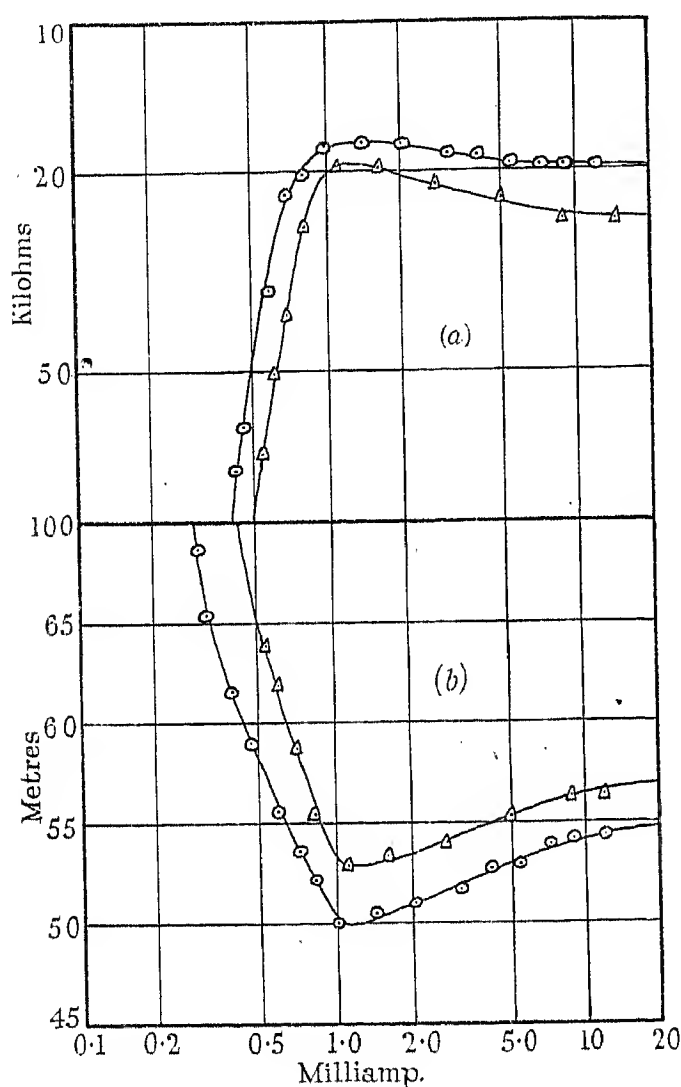


Fig. 6

(a) Variation of negative resistance with filament emission. Anode voltage, 100 volts. Field strength, 1 790 gauss. Amplitude, 13.6 volts (r.m.s.). Tilt zero —○—○—. Tilt 4° —△—△—

emission, the measurements being taken with a constant value of resistance. It will be seen that I_a and E^2/R reach maximum values when I_e is near the optimum value. A point of interest is that I_a is normally only slightly less than I_e , and thus the input current to the valve must be nearly constant over the cycle, and that its wave-form must be sensibly rectangular: it is probable that most of the current flows alternately to either anode segment during the half-cycle when it is at the lower potential. Attempts to verify this directly by observing the wave-form of the input feed current by an oscillograph or by determining the Fourier components (if any) by suitable tuned circuits have only been partly successful. When this is considered with the effect of voltage amplitude and the small radius of the electron cloud it seems that the

electron motion induces a constant radio-frequency current in the anode circuit while the input current assumes a value directly related to the power E^2/R . It should be stated that the optimum values of I_e , particularly at the longer wavelengths, are only a very small fraction of the normal space-charge-limited current appropriate to the steady anode potentials, and thus there appears to be some condition in the valve which tends to increase the space charge.

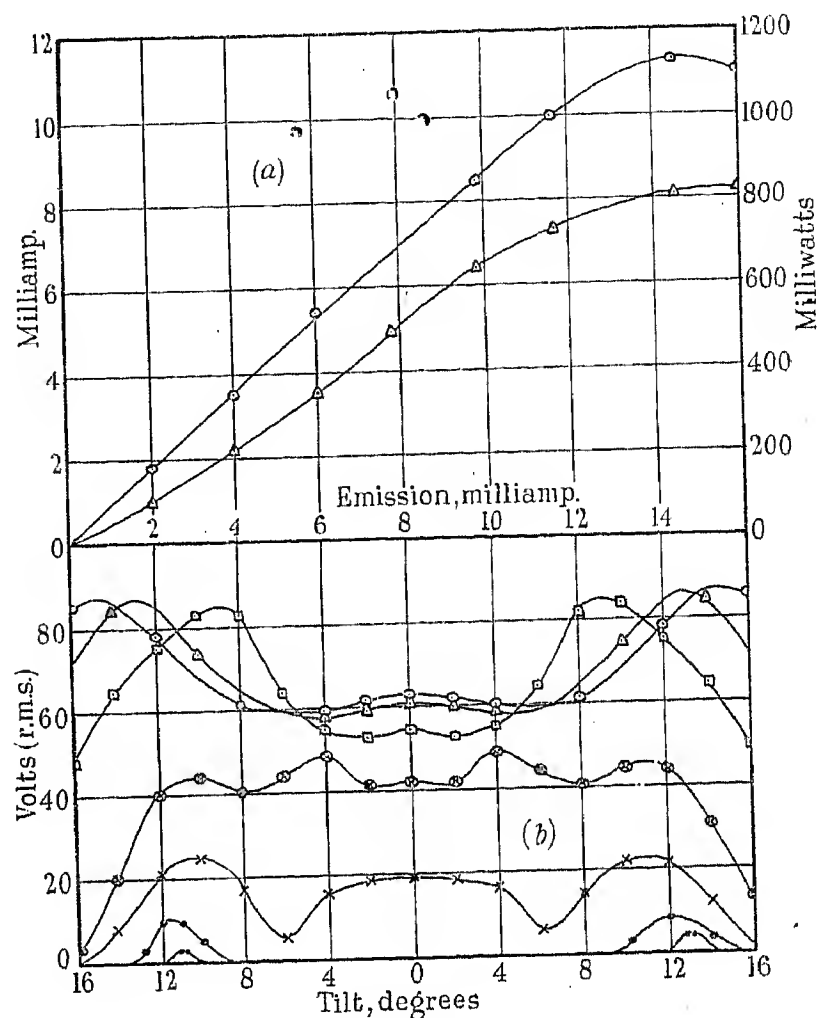


Fig. 7

(a) Variation of input current and of power with filament emission. Resistance, 18.6 kΩ. Tilt, zero. Input current —○—○— Power, —△—△—

(b) Variation of amplitude with angle of tilt. Anode voltage, 100 volts. Wavelength, 61.8 m. Field strength, optimum. Resistance, 115 kΩ. Emission 10 mA —○—○— Emission 5 mA —△—△— Emission 2 mA —□—□— Emission 1 mA —⊕—⊕— Emission 0.5 mA —×—×— Emission 0.2 mA —●—●— Emission 0.1 mA —●—●—

It will have been seen that the changes due to increasing α (angle of tilt of field) are similar to those due to decreasing the emission, a result in agreement with one of the known effects of tilt on space charge. Small tilts are found not to cause appreciable changes in the valve properties (i.e. zero tilt is always a maximum or minimum point), but when α is large the effects are complex, as shown in Fig. 7(b), where the voltage amplitude, for a convenient value of resistance, was measured as a function of tilt. It will be seen that at zero tilt the amplitude rapidly decreases with emission when this is less than about 5 mA, and if I_e is less than about 0.25 mA there is no amplitude for which $R = -115$ kΩ. The humps near $\alpha = 12^\circ$ show that tilt can decrease the negative resistance in certain cases, and this effect is related to the

electron-cloud radius since when this is large (as when H and hence λ are small) tilt causes no improvement. This agrees with theory since, when the cloud radius is small, tilt causes the ends to approach more closely to the anode, without, however, causing the electrons to collide—as happens when the cloud is originally just within the anode sheath. It was further noticed that the optimum value of H decreases as α increases, and it is of interest to

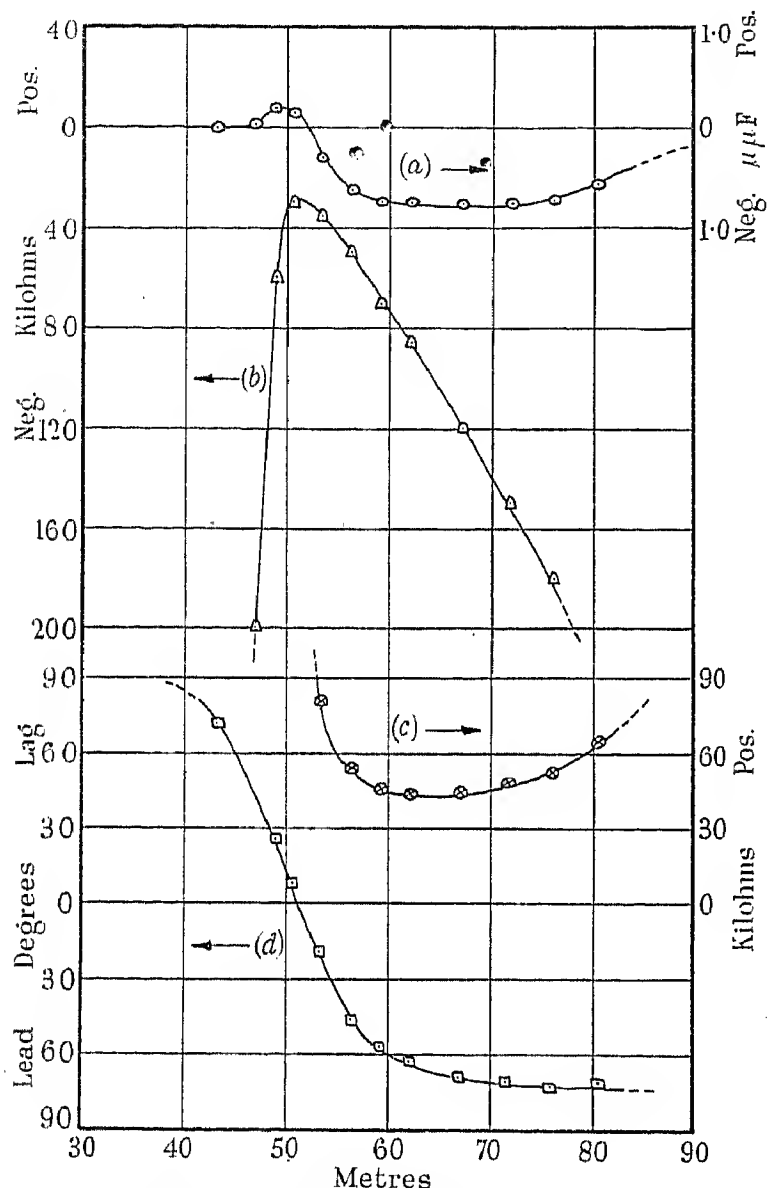


Fig. 8.—Variation of (a) change in valve capacitance, (b) negative resistance, (c) reactance, and (d) phase angle, with wavelength.

Anode voltage, 100 volts.
Filament emission, 10 mA.
Field strength, 1 790 gauss.
Amplitude, 13.6 volts (r.m.s.).

Capacitance —○—○—
Resistance —△—△—
Reactance —□—□—
Phase angle —×—×—

point out how apparent dissymmetry in the valve is much reduced as the emission increases—a fact not unique to the results of Fig. 7(b).

(e) Reactance and Phase Angle

It is known (J. S. McPetrie⁶ and A. Giacomini⁸) that in the resonance regime the impedance of the magnetron has a reactive component, and this was measured in terms of the difference of the necessary tuning capacitance with the magnetron filament cold and hot. The apparent resistance and capacitance are shown as a function of wavelength in Fig. 8, from which it will be seen that the magnetron operation in general causes an apparent decrease of electrode capacitance. The corresponding

curves of reactance and phase angle are also shown; it will be seen that the latter changes from near 90° lead to near 90° lag, and this is because $-R$ tends to infinity more rapidly than C (change in capacitance) tends to zero. Measurements show that C varies inversely as the amplitude, and hence the phase angle is independent of amplitude. The phase angle is also independent of wavelength provided this is accompanied by proportionate changes of field strength. Since $-R$ has been shown to vary as λ , it follows that c is sensibly independent of wavelength, its greatest value being of the order 1 $\mu\mu\text{F}$ in this valve.

(f) Generation of Oscillations

For any assigned load resistance the power output can be calculated when the amplitude is known, and this output is found to reach a maximum as the field strength

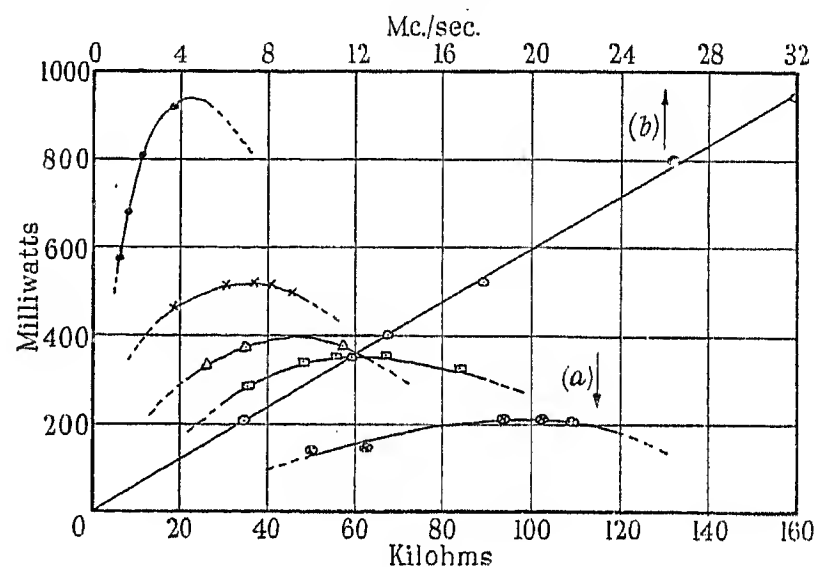


Fig. 9

- (a) Variation of power with load resistance at various different frequencies.
(b) Variation of maximum power frequency.

Anode voltage, 200 volts.
Filament emission, 10 mA.
13.4 Mc/s., 22.35 m. —△—△—
11.2 Mc/s., 26.75 m. —□—□—
9.27 Mc/s., 32.2 m. —○—○—
6.9 Mc/s., 43.30 m. —×—×—
17.8 Mc/s., 16.85 m. —×—×—
Maximum power —○—○—

is increased. This maximum output is shown as a function of load resistance in Fig. 9(a) for five wavelengths, and it will be seen that each rises to a blunt maximum. The optimum value of field does not, however, change much over a wide range of load resistance. Determination of I_a makes it possible to calculate the efficiency at maximum output, and this is found to be of the order of 40 %–60 % and is sensibly independent of wavelength. It may be deduced from Fig. 4 that the efficiency in general is nearly independent of amplitude and resistance, but it is found to vary with anode voltage and filament emission. The maximum output is shown as a function of frequency in Fig. 9(b), and results in a linear relation. The optimum load decreases linearly with wavelength as in Fig. 5. The magnetic field at maximum output is shown in Fig. 10(a) as a function of wavelength and in Fig. 10(b) as a function of anode voltage, and these linear relations result in a value of K that differs little from a mean of 292. When generating oscillations in this regime under conditions where the input is large the magnetron shows the well-known phenomenon of additional heating of the filament. If under certain conditions a continuous-wave output is not essential the

restrictions imposed by anode dissipation and filament heating can be overcome by applying the anode supply voltage in the form of sharp rectangular pulses, the voltage of which can be up to several times the normal value. An additional advantage is that the minimum wavelength is considerably reduced, as indicated previously, and using a small 4-segment valve rated at 150 watts, peak outputs of several kilowatts have been obtained on a wavelength of 25 cm.

The relation between power (E^2/R) and I_e shown in

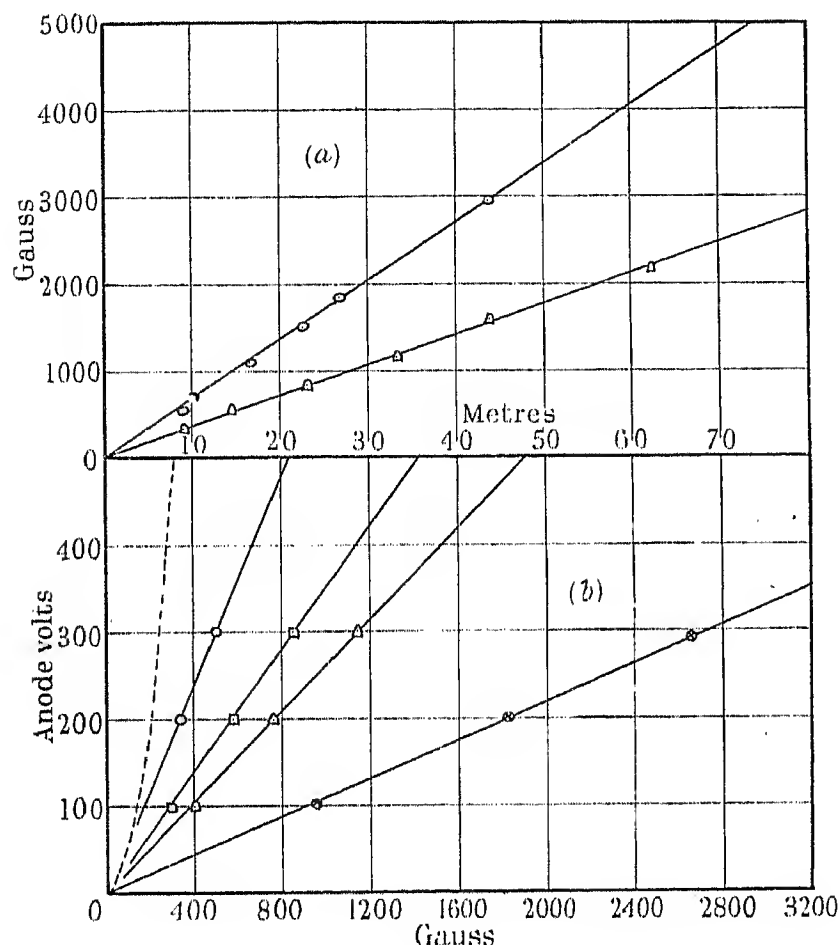


Fig. 10

- (a) Variation of field strength for maximum power and for minimum wavelength, with wavelength.
 Anode voltage, 200 volts. Maximum power —○—○—
 Anode voltage, 100 volts. Minimum wavelength —△—△—
- (b) Variation of anode voltage with field strength, for maximum power.
 Cut-off condition ————
 Wavelength 4.8 m. —○—○— Wavelength 8.0 m. —□—□—
 Wavelength 11.0 m. —△—△—
 Wavelength 26.8 m. —⊕—⊕—

Fig. 7(a) indicates that modulation by control of the space current (as by means of a suitable control grid) is possible provided the current is below the optimum value, but the linearity is not good and the mean output would be low. Fig. 3 shows that anode modulation is possible, both when the amplitude increases with V and when it decreases. In the former case the modulation depth is limited (and sometimes zero), and if this limit is exceeded a hysteresis effect occurs which at the longer wavelengths is sufficient to prevent the oscillations from building up again without circuit readjustment. Similar results would be expected from field-strength modulation, but it has been shown that if H and V are altered in the same ratio then the amplitude for a given resistance alters similarly: thus nearly full and linear modulation is possible in this manner. It is apparent from Fig. 4(a) that linear modulation is also possible by variation of the

load resistance by a suitable modulating system, but the depth is restricted to an extent depending on the field.

The frequency stability as a property of the magnetron has been measured in the dynatron regime by the author,¹ who found that in the neighbourhood of the best operating conditions the stability is of the order 200 parts in 10^6 . Small variations in valve resistance due to changes in the operating conditions have an effect on the generated frequency, but the curves of Fig. 2 suggest that the behaviour of the magnetron in the resonance regime in respect of frequency stability should be the same as that for any "dynatron type" generator. Frequency-changes due to small variations in the valve reactance can be reduced by the use of circuits with a small L/C ratio and low values of rejector resistance, but these conditions are not conducive to good circuit stability.

Consideration of Fig. 4(a) shows that self-oscillation is not possible when the load resistance is less than a certain minimum value which depends on H , but if a voltage of sufficient magnitude is applied the valve exhibits negative resistance at the wavelength of the applied potential. Thus the effective value of the load resistance to the source of fluctuating potential is reduced, resulting in amplification. For example, if the load resistance is made 60 k Ω with $H = 2260$ then for an amplitude of 40 volts (r.m.s.) the negative resistance is 78 k Ω , making the effective load resistance 260 k Ω . The driving power is 6.1 mW and the output is 26.7 mW, resulting in a power amplification of 6.5 db. The linear relation between negative resistance and amplitude shows that the valve would amplify a wave with a depth of modulation depending on the field strength, but the modulation wave would be distorted and, since the driving power varies during the cycle, it would be necessary for this stage to have a low internal resistance to avoid further distortion.

Fig. 4(a) also suggests that, for any given conditions, knowledge of the voltage amplitude when the valve and a given circuit act as a generator determines the rejector resistance of the circuit, and as a result of the linear relation between resistance and wavelength in the magnetron it is possible to calibrate it at long wavelengths and measure circuit resistances at much shorter wavelengths. Although the curves shown apply to symmetrical circuits similar ones could be derived for the case in which the valve is operated in an unsymmetrical manner.

(4) IMPEDANCE IN THE ELECTRONIC REGIME

(a) Filament Emission and Angle of Tilt

Since the properties are practically independent of any external impedance the valve was operated as a self-excited generator, the wavelength of the external oscillation being carefully measured. The circuit used was a pair of parallel wires several wavelengths long (λ about 30 cm.) kept away from other objects, the H.T. input being by means of a sliding bridge in the form of a large metal screen, and the idle portion of the line being terminated by a suitable resistor. The amplitude was usually indicated by a thermocouple and millivoltmeter placed near the valve, the position being adjusted for maximum millivoltmeter reading. The wavelength was measured by noting the bridge positions for maximum

amplitude, and the mean of several half-wavelengths was taken. As the resistance in the electronic regime is particularly sensitive to changes in magnetic field the latter was accurately determined by using an electromagnet with a stalloy yoke so that hysteresis was reduced to a minimum, and by careful calibration with a fluxmeter. The presence of undesired long-wavelength oscillations, inherent to the form of circuit adopted, was eliminated by suitable adjustment of emission and tilt.

It is known that the amplitude depends considerably on the angle of tilt, and it was found that the optimum tilt varied with the filament emission in the manner shown in

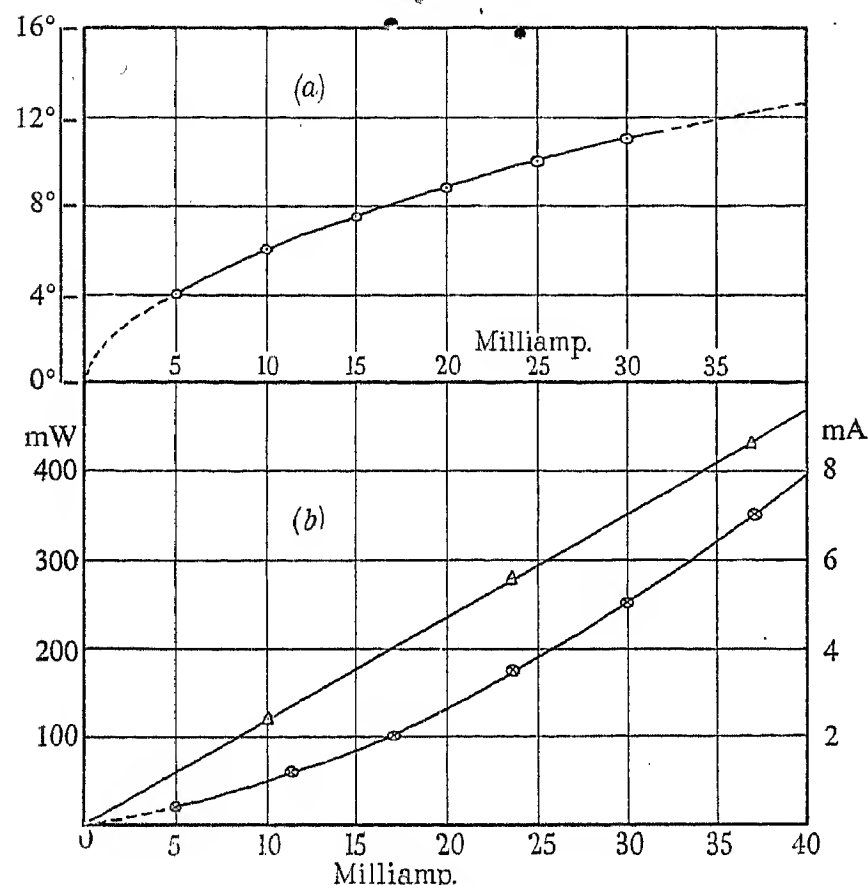


Fig. 11

(a) Variation of optimum angle of tilt with filament emission

(b) Variation of anode-current increase and of equivalent filament heating with anode current.

Anode voltage, 700 volts.
Field strength, 405 gauss.
Wavelength, 30 cm.

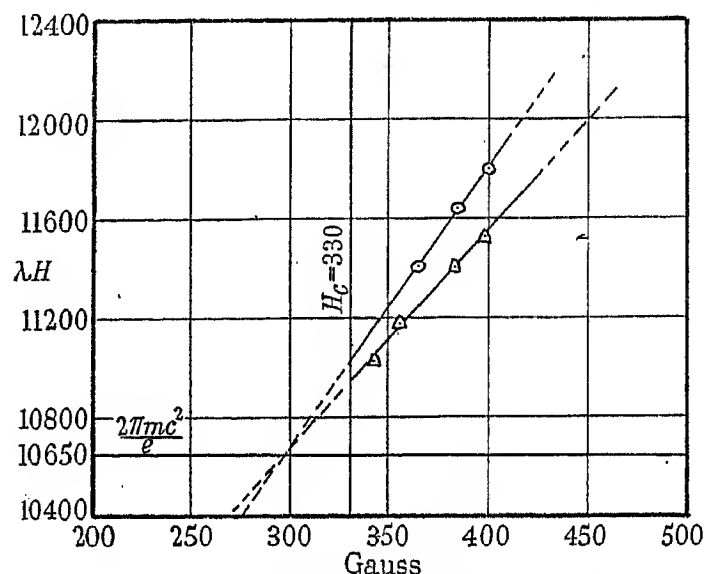
Optimum tilt
Anode-current increase
Filament heating

—○—○—
—⊕—⊕—
—△—△—

Fig. 11(a) for a given set of operating conditions. Thus for vanishingly small emissions the optimum tilt appears to be zero, although the valve resistance would then be very high. Thus tilt is necessary to reduce the space charge caused by the larger emissions, an effect which is in agreement with theory. It is likely that the advantage of slight tilt is the reduction in resistance previously discussed, although the fact that the magnetic field only just exceeds the cut-off value means that a large number of electrons collide with the anode, resulting in low efficiency. The amplitude increases to a maximum with emission and tilt and then falls for larger currents. Thus there appears to be some mechanism in the valve, as noted for the resonance oscillations, which increases the normal space charge, since saturation should not occur until the emission is of the order of several amperes with the high anode-voltages employed.

The determination of the valve resistance itself is difficult owing to the very short wavelengths and the

finite size of electrodes, which make the valve equivalent to a small uncertain length of line. It was found that the amplitude indication was little affected by changing the line impedance from 250 to 500 ohms and that in order to obtain maximum brightness of a load lamp whose steady-current resistance was 10 ohms it was necessary to place it near a voltage antinode. Since the power outputs were of the order of 1 watt and the voltage amplitude appeared to be only a few volts it would seem that the resistance has a very low value (in the neighbourhood of 20 ohms) at this wavelength. Extrapolation of the resistance values found at the longer wavelengths in the resonance regime would indicate such a resistance, and it is probable that the magnetron resistance is always low near the cut-off condition. This would be explained by

Fig. 12.—Variation of λH (in cm. gauss) with field strength

Anode voltage, 600 volts.
Emission 27 mA, tilt 9.5° —○—○—
Emission 14 mA, tilt 8.0° —△—△—

the fact that the electrons at the outer portion of their orbits pass very close to the segment gaps and experience the maximum force due to any potential differences.

(b) Wavelength and Magnetic Field

It is well known⁹ that negative resistance in the electronic regime exists at wavelengths such that λH is a constant of about 11 000, and, moreover, that this value appears to be closely related to the transit time of the electrons.¹⁰ The values of this product were measured under different conditions, and the variation of λH with H is shown in Fig. 12 to be sensibly linear, the required field-strengths being slightly greater than the cut-off value. Fig. 13 shows that λH increases with the emission but tends to a minimum when this becomes small. The corresponding curves of tilt (also shown) result in an effect to be expected from Fig. 11(a).

It will be observed that the minimum values to which λH tends are generally within the range 11 000–11 400, the lower values relating to conditions in which the space charge would be expected to be less. It is known that if the magnetic field is such that the electrons just miss the anode then when the cathode radius is made zero the electron transit-time tends to the value

$$T = \frac{2\pi mc}{He}$$

for vanishingly small emissions, and to the first order this time is not changed by small angles of tilt. A wave with this periodic time gives $\lambda H = 10\,650$, and for the cathode radius of the valve used graphical integration of A. W. Hull's equations gives a value of λH about 15 % greater.

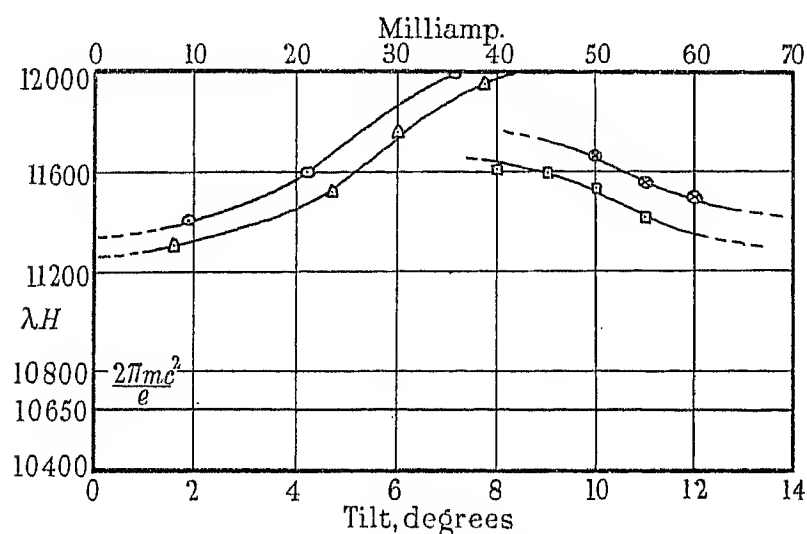


Fig. 13.—Variation of λH (in cm. gauss) with filament emission and with angle of tilt.

Field strength, 384 gauss.
Anode voltage 600 volts, tilt 8° —○—○—
Anode voltage 600 volts, tilt 10° —△—△—
Anode voltage 600 volts, emission 21 mA —□—□—
Anode voltage 630 volts, emission 36 mA —⊕—⊕—

F. B. Pidduck¹¹ shows that the effect of space charge in the cylindrical (and in the planar) magnetron is to increase the electron transit-time, and while the observed changes in λH can be qualitatively explained by changes in space charge it seems that the observed value is less than would be expected from theory. It is not possible to arrive at any definite conclusion since the oscillations

to be high since oscillations are found only at comparatively high anode voltages, and in some cases large angles of tilt and critical values of filament emission are necessary. Some typical results are given in Table 2.

The value of $\lambda H/10\,650$ is usually known as the "order of oscillation," and is taken as unity for the normal electronic oscillation. The first four results show that oscillation can take place when, as in the electronic regime, λH tends to be constant, although the order of oscillation is very high. All the results show that intermediate values of $\lambda V/H$ are possible, but the fact that the optimum tilts and emissions are different makes it difficult to come to any definite conclusion regarding the relation between them. No extensive measurements were made of the properties of the valve under these conditions, but it was noted that they tended to be those associated with the resonance oscillations as well as the electronic type. It is important that these minor oscillations show properties similar to those of the other two regimes, since it points to a similarity between the latter. Thus many of the valve properties determined at longer wavelengths could be applied, at least qualitatively, to the electronic regime of negative resistance, and it is possible that they could be applied in part to electronic oscillations occurring in thermionic valves in general.

(c) Additional Filament Heating

As with resonance oscillations, additional filament heating occurs, which is revealed by the feed current exceeding the value for H zero. This phenomenon has been partly examined by O. Pfetscher and W. Puhlmann¹² and A. P. Maidanov.¹³ Since I_a is only slightly less than I_e any observed increase in I_a is due mainly to an increase of emission. Fig. 11(b) shows this increase and the

Table 2

λ	V	H	α	I_e	$\lambda V/H$	$\lambda V/(44H)$	λH	$\lambda H/10\,650$	$-R$
cm.	volts	gauss	degrees	mA					kΩ
370	200	1 120	17	6	66	1.5	415 000	38.9	Approx. 20
370	300	1 140	3.5	2	97	2.2	420 000	39.4	
370	400	1 120	17	6	132	3.0	415 000	38.9	
370	500	1 100	8	5	168	3.8	407 000	38.2	
370	300	371	0	1.5	297	6.8	137 000	12.8	
370	300	640	8	15	173	3.9	237 000	22.2	
370	300	1 680	16	20	66	1.5	620 000	58.2	

generally occur at fields exceeding the cut-off value, and with small alternating voltages between the segments it is difficult to estimate the transit time under such conditions.

As in the case of resonance oscillations it is possible to calculate the values of $\lambda V/H$ over the range of negative resistance. In particular, the value for maximum output varies only slightly and has a mean of 44 which is about one-seventh the value of 292 for maximum output of resonance oscillations. This suggests that there may be other regimes of negative resistance with such integral relations, and some of these have been found. The resistances of the magnetron in these minor regimes tend

equivalent filament heating power (derived from the emission characteristic) as a function of anode current for a constant anode voltage. This effect increases with the input to the valve, and since the output falls appreciably for large emissions it is evident that this effect can occur when there is no external evidence of oscillation.

The filament was heated from a sensibly constant-current source and the changes in battery filament heating due to resistance variations were determined by a potentiometer and millivoltmeter. After the equivalent heating has been corrected for this some energy remains, namely that imparted to the filament during operation and which must come from the anode supply. Moreover,

the filament-resistance changes correspond to those which would occur if the increased anode current were entirely due to an increase in filament emission; and thus in this case any effects due to secondary emission, positive-ion current, or other causes are negligible.

This energy is expressed in Fig. 14(a) as a function of changes in length of the external circuit. It will be noted that this effect is greater when the external output is a

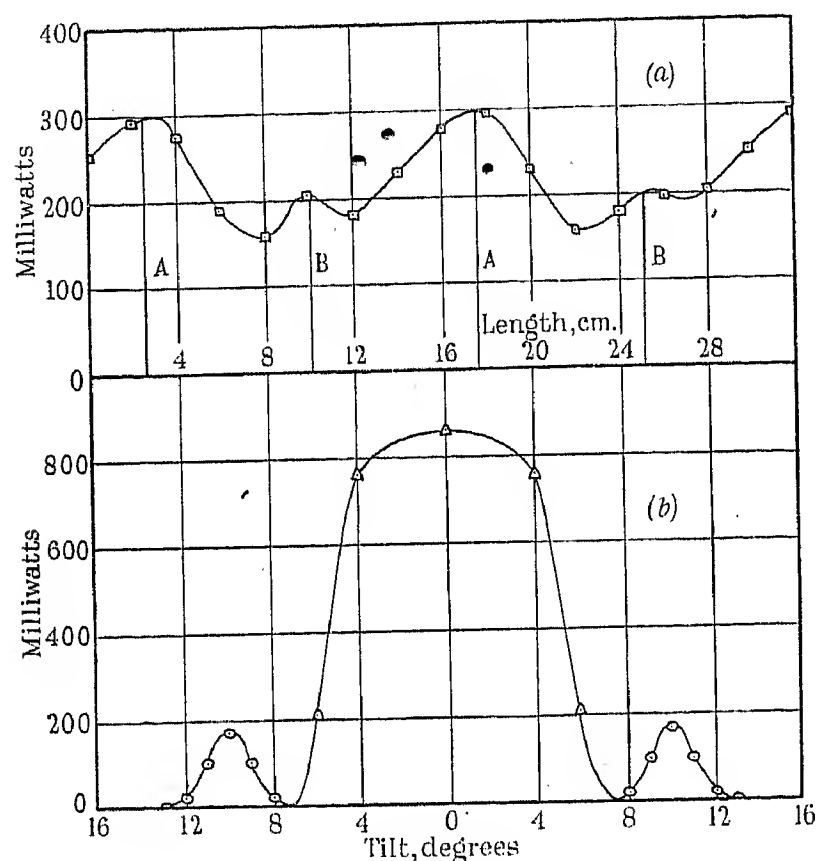


Fig. 14

- (a) Variation of filament heating with change in length of external circuit.
 (b) Variation of filament heating with angle of tilt.

Anode voltage, 700 volts.
 Field strength, 381 gauss.
 Filament emission, 35 mA.
 "A" represents minimum external output.
 "B" represents maximum external output.
 Wavelength 30 cm., tilt 10° —□—□—
 Wavelength 30 cm. —○—○—
 Wavelength 350 cm. —△—△—

minimum (and actually nearly zero), and suggests that the mechanism causing this heating would be present with the anode segments short-circuited. The rises in anode current in this experiment were of the order shown in Fig. 11(b). Fig. 14(b) shows this heating energy as a function of angle of tilt, and some results for the larger resonance regime heating are also included. It would seem that this heating is due to the electrons returning to

the filament with higher velocities than those with which they left, since it can be demonstrated⁴ in other ways that it is possible for the electrons in the course of their orbits to have greater velocities than those given by simple calculation. It is uncertain, however, whether it is a necessary condition that oscillation shall be present.

(5) CONCLUSIONS

A description has been given of experiments made to measure the impedance of the magnetron and to investigate its special properties in the three regimes of oscillation which are usually recognized as distinct. Many direct properties of the valve have been found and these have been discussed, and where possible agreement or conflict with the known theory of the magnetron has been pointed out. There appears to be experimental evidence which strongly suggests that these regimes are not entirely distinct, and that the valve properties may differ in them only because of the varying effects due to electron motion or allied phenomena.

(6) ACKNOWLEDGMENTS

The work described in the paper was carried out in the Engineering Laboratory of the University of Oxford, and the author is indebted to Mr. E. B. Moullin, M.A., Member, for his advice and interest in the experiments and for help in the preparation of the paper.

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INSTITUTION NOTES

THE LATE COLONEL R. E. B. CROMPTON

A Memorial Service for the late Colonel R. E. B. Crompton, C.B., F.R.S., Past-President, Honorary Member and Faraday Medallist, arranged by The Institution, was held at St. Margaret's Church, Westminster, on Thursday afternoon, 22nd February, 1940, and was attended by a large number of his friends and of representatives of the various societies and organizations with which he had been associated. Canon V. F. Storr officiated.

At the Ordinary Meeting of The Institution held on the same day, the President paid a tribute to Colonel Crompton's outstanding services to the electrical profession and he asked the members present to stand in silence for a few moments as a mark of esteem.

I.E.E. WIRING REGULATIONS

A number of alterations and additions to the Eleventh Edition of the I.E.E. Regulations for the Electrical Equipment of Buildings were approved by the Council on the 22nd February for publication as a Supplement to the Regulations.

Copies of the Supplement can be obtained free of charge, on application to the Secretary, for insertion in existing copies of the Regulations.

VOLUNTARY NATIONAL SERVICE—CENTRAL REGISTER

Special Panels of the Electrical Engineering Sub-Committee have, from time to time, recommended the names of members for vacant appointments notified through the Central Register.

The Institution is anxious to keep its records up to date, and the Secretary would therefore be glad if members who have been offered positions through the Central Register would inform him of their decision, irrespective of whether the offer is accepted or refused.

COOPERS HILL WAR MEMORIAL PRIZE AND MEDAL

The triennial award of the above Prize and Medal falls this year to The Institution, and the Council have decided to invite members to submit for consideration a paper on any subject coming within the scope of electrical science or electrical engineering and their applications. Papers submitted must be specially written for the purpose of the competition and must reach the Secretary not later than the 1st October, 1940. Only Corporate Members who were under 35 years of age on the 1st January, 1940, are eligible to compete.

Full particulars will shortly be circulated to all Corporate Members.

SCHOLARSHIPS

The Secretary desires to draw the attention of members to the following Institution Scholarships. The closing date for receiving nominations for this year's awards is the 15th April. Any member desirous of obtaining more detailed information should apply to the Secretary.

Duddell Scholarship (value £150 per annum for 3 years).

Open to British subjects under 19 years of age on the 1st July who have passed a matriculation or equivalent examination, and who desire to take up a whole-time day course in electrical engineering.

Preference will be given to candidates whose fathers or a near relative are, or have been, members of The Institution.

Ferranti Scholarship (value £250 per annum for 2 years).

For whole-time research or post-graduate work. Open to British subjects under 26 years of age on the 1st July, who have been Students or Graduates of The Institution for at least 2 years and have taken either (a) a whole-time course in electrical engineering of at least 3 years and obtained a degree or diploma; or (b) a whole-time course in science of at least 3 years and obtained an honours degree, provided that in the final examination for such degree they have passed in "physics," or "electrochemistry," or "electrometallurgy."

Preference will be given to candidates whose fathers are, or have been, members of The Institution.

Swan Memorial Scholarship (value £120 for 1 year).

The conditions are similar to those for the Ferranti Scholarship, except that the age limit is 27 years on the 1st July and that candidates need not be members of The Institution. Preference will be given to candidates who were born in the County Borough of Sunderland, or resided there for at least 7 years, or were educated at Sunderland Technical College.

Silvanus Thompson Scholarship (value £100 per annum, plus tuition fees, for 2 years).

Open to British subjects who have served a minimum apprenticeship (or its equivalent) of 3 years at an approved works and are under 22 years of age on the 1st July, and who desire to take up a whole-time day course in electrical engineering.

William Beedie Esson Scholarship (value £120 per annum; tenable for 2 years, renewable in approved cases for a third year).

The conditions are similar to those for the Silvanus Thompson Scholarship.

BRITISH STANDARDS

The Secretary has been asked by the British Standards Institution to draw attention to the following new and revised Specifications:—

Voltages (B.S. No. 77).

Since the publication in 1932 of the third edition of this British Standard, the development in a.c. transmission and distribution has brought about considerable changes in practice, and the revised edition of B.S. No. 77 recently issued takes account of this progress.

The chief change between the old and the revised specification is the substitution of two standard voltages:

"system voltage" and "declared voltage" for the 4 voltages included in the 1932 edition.

System voltage is defined as "the voltage between lines for which the system is designed and installed," while the "declared voltage" is "the voltage at the consumer's terminals declared by the undertaker."

In the interests of general standardization, the Specification is not now confined to new systems.

A revised list of standard voltages is given.

Copies of this British Standard can be obtained from the British Standards Institution, Publications Department, 28, Victoria Street, London, S.W.1., price 1s. each (1s. 2d. post free).

Glossary of Terms used in Electrical Engineering (B.S. No. 205—1936).

An addendum has recently been issued to the above Glossary. It takes the form of a Section dealing with terms and definitions used in radio direction-finding. These terms and definitions have been published as a British Standard, with the approval of the appropriate B.S.I. Committees, at the request of the Department of Scientific and Industrial Research, and were prepared by the Direction-finding Committee of the Radio Research Board, of that Department. They will be included in the body of the Glossary when that publication is revised.

Copies of this Addendum can be obtained from the B.S.I., price 1s. each (1s. 2d. post free).

Air-break Switches and Circuit-breakers (B.S. Nos. 861 and 862).

Two new Specifications, B.S. No. 861 and B.S. No. 862, have been issued. These combine in two documents material originally published in 6 specifications, as follows:—

B.S. No. 861 covers revisions of—

B.S. No. 109—1934. Air-break Knife Switches and Air-break Isolating Switches.

B.S. No. 124—1934. Totally-enclosed Air-break Switches.

B.S. No. 126—1930. Flame-proof Air-break Switches.

B.S. No. 862 covers revisions of—

B.S. No. 110—1934. Air-break Circuit-breakers.

B.S. No. 127—1930. Flame-proof Air-break Circuit-breakers.

B.S. No. 130—1934. Totally-enclosed Air-break Circuit-breakers.

It is felt that this will facilitate the use of the Specifications, many clauses of which were common to all.

Copies may be obtained from the B.S.I., price 2s. each (2s. 2d. post free).

Gauges for A.R.P. Lighting (BS/ARP 30).

One of the difficulties in complying with the provisions of the various regulations and specifications in connection with A.R.P. lighting is that the illumination values are expressed in foot-candles. The measurement of illumination in terms of foot-candles presents no difficulties in properly equipped laboratories, but it is quite a problem to evaluate illumination "on site," particularly when the level of illumination is of the low order

imposed by A.R.P. restrictions. For many purposes it is not required that quantitative measurements should be made, but merely that tests be made to ascertain whether the illumination is in excess of, or less than, the prescribed value. With this in view, gauges for checking low values of illumination have been developed, and a British Standards Specification (BS/ARP 30) has been published. The nominal values of illumination for which gauges are prescribed in the specification are 0.0002, 0.002, 0.02 and 0.2 foot-candle, and means may be provided for enabling more than one of these values to be gauged with the same instrument. The specification aims at ensuring the necessary accuracy combined with portability, but leaves the manufacturer free to develop his own design. An appendix giving notes on the essential parts of the gauges, and on the use of gauges, is included. Copies of this specification can be obtained from the B.S.I., price 2d. (3d. post free).

War-time Street Lighting (BS/ARP 37).

Although the installation of the new form of street lighting is in many parts of the country only just beginning, a revised edition of BS/ARP 37 has been issued. This revision, however, does not modify the provisions of the original edition (dated December, 1939) but extends them in a very useful direction. There are two main additions, namely:—

(a) The inclusion of standard curves of light distribution for fittings intended for mounting heights between 9 ft. and 14 ft. (nominal mounting height 10 ft.) and for use where the spacing is less than 100 ft. but is not less than 50 ft. These fittings are designated "10 ft. SS" to distinguish them from the 10-ft. nominal-mounting light-fittings intended for spacings over 100 ft.

(b) An appendix has been added, containing notes on the design and testing of fittings purporting to comply with the specification. These notes are given primarily for the guidance of those concerned with the design and production of fittings for which certification is desired, but they will doubtless prove of interest to a much wider circle of readers of the specification as they deal generally with photometric measurements at very low candle-powers.

Copies of the revised BS/ARP 37 can be obtained from the B.S.I., price 6d. (8d. post free).

MEMBERS ON SERVICE WITH H.M. FORCES AND WITH THE ALLIES

(THIRD LIST)*

(NOTE.—The Secretary will be glad to receive, for publication in subsequent lists, the names of other members of The Institution who are serving with His Majesty's Forces or with the Allies, together with particulars of their rank and the unit in which they are serving.

It is also proposed to publish lists of promotions, transfers, military honours awarded, etc.† All such particulars, both in regard to a member himself and in connection with other members of whom he may have knowledge, should be sent to the Secretary as early as possible so that the Institution records can be kept up to date.)

* See *Journal I.E.E.*, 85, p. 653, and 86, p. 99.

† The first list of promotions and transfers will be found on page 311.

Members

<i>Name</i>	<i>Corps, etc.</i>	<i>Rank</i>
Ailleret, P. M. J.	Engineers Corps (French Army)	Captain
Dickinson, J.	Reception Unit	Captain
Glendenning, S. E.	Royal Engineers	Major
Jones, J. E.	Royal Engineers	Lieutenant
Pooley, L. A. C.	Royal Engineers	Sec. Lieut.
Reading, J.	Royal Signals	Captain

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Clay, R. A.	Royal Air Force	Flying Officer
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Collier, J. T.	Royal Engineers	Sec. Lieut.
Collingbourne, H. L.	Royal Signals	Captain
Colvin-Smith, P. M.	Royal Engineers	Sec. Lieut.
Cunliffe, E. N.	Royal Engineers	Lieutenant
Daniel, C. S.	Royal Navy	Captain
de Salis, A. F.	Royal Navy	Captain
Dunford, A.	Royal Marines	Lieutenant
Entwistle, J.	Royal Engineers	Major
Farrell, J. F. E.	Royal Signals	Lieutenant
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Fisher, J.	Royal Navy	Lieutenant
Graham, A.	Royal Engineers	Sec. Lieut.
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Hibbs, N. L.	Royal Signals	Sec. Lieut.
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Ingham, F.	Royal Air Force	Flt.-Lieut.
Jarratt, R. C.	Royal Engineers	Lieutenant
Johnston, C. S.	Royal Army Service Corps	Lieutenant
Jones, J. G.	Manchester Regiment	Captain
Lemon, E. O.	Royal Naval Volunteer Reserve	Sub-Lieut.
London, P.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)
McDonald, R. E. W.	Royal Engineers	Lieutenant
Markland, J. D.	Royal Naval Volunteer Reserve	Sub-Lieut.
Mayes, E. A.	Royal Artillery	Captain
Metson, G. H.	Royal Signals	Lieutenant
Morcom, H. G.	Royal Air Force (V.R.)	Squadron Leader
Patterson, J. H.	Royal Artillery	Captain
Podoski, J.	Polish Army	Lieutenant
Rees, T.	Royal Naval Volunteer Reserve	Sub-Lieut.
Rendle, H. B.	Royal Naval Volunteer Reserve	Sub-Lieut.
Reynolds, J. A. E.	Royal Engineers	Captain
Sleeman, H.	Royal Engineers	Colonel
Stanley, V. E.	Royal Signals	Lieutenant
Wethered, H. E.	Royal Navy	Lieut.-Comdr.
Whatman, A. B.	Royal Signals	Captain
White, E. J.	Royal Engineers	Sec. Lieut.

Associates

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Featherstone, W. A. E.	Royal Air Force	Flt.-Lieut.
Hazeltrove, H.	Royal Navy	Chief Petty Officer Telegraphist
Henning, A. J.	Royal Engineers	Lieutenant
Kennedy, A. C.	Royal Engineers	Captain
Robertson, L. R.	Royal Navy	Sub-Lieut.
Sillar, L. G.	Royal Engineers	Captain
Smith, N. A.	Royal Artillery	Lieutenant
Wellingham, H. J.	Royal Artillery	Captain

Graduates

<i>Name</i>	<i>Corps, etc.</i>	<i>Rank</i>
Abbott, R. M. F.	Royal Naval Volunteer Reserve	Sub-Lieut.
Allen, D. C.	Royal Engineers	Corporal
Armstrong, G.	Royal Naval Volunteer Reserve	Sub-Lieut.
Baker, M. W.	Royal Signals	Signalman
Bawtree, H. M.	Royal Signals	Cadet
Beatson, C. J.	Royal Artillery	Gunner
Berridge, E. J.	Royal Horse Artillery	Gunner
Birchenhough, H.	Royal Army Ordnance Corps	Lieutenant
Boundy, J. R.	Royal Air Force	Flying Officer
Bowyer, F. P.	Royal Naval Volunteer Reserve	Sub-Lieut.
Brook, E. R.	Royal Navy	Telegraphist
Calderara, P.	Royal Naval Volunteer Reserve	Sub-Lieut.
Callender, M. W.	Royal Naval Volunteer Reserve	Sub-Lieut.
Catto, E. H.	Royal Engineers	Sapper
Collins, F. H.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)
Cooper, S.	Royal Army Ordnance Corps	Lieutenant
Davis, T.	Royal Artillery	Sergeant
Dean, J. A.	Royal Air Force	Sergeant
Degerdon, M. E.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)
Fenn, R. W.	Royal Naval Volunteer Reserve	Sub-Lieut.
Fielding, T. J.	Royal Signals	Sec. Lieut.
Furse, C. W.	Royal Air Force	Pilot Officer
Garson, A. A.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)
Gates, N. P.	Royal Signals	Sec. Lieut.
Gates, R. E.	Royal Signals	Signalman
Goff, H. S. H.	Royal Signals	A/Sergeant
Gore, W. E.	Royal Air Force	Flying Officer
Gosling, J. C.	Royal Signals	Signalman
Hammond, J. D. le B.	Royal Army Ordnance Corps	Lieutenant
Headland, R. C. C.	Royal Engineers	Lance-Corporal
Hewitt, W. M.	Royal Engineers	Sec. Lieut.
Hickling, C. G.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)
Horn, J. G.	Royal Naval Volunteer Reserve	Sub-Lieut.
Hughes, D.	Royal Army Medical Corps	Private
Hutchinson, G. P.	Royal Naval Volunteer Reserve	Sub-Lieut.
Iago, J. M.	Royal Naval Volunteer Reserve	Sub-Lieut.
Ingham, L.	Royal Naval Volunteer Reserve	Sub-Lieut.
Jackson, G. B.	Royal Engineers	Sapper
Jackson, S.	Royal Engineers	Sergeant
James, D. N. A.	Royal Army Ordnance Corps	Lieutenant
Kibblewhite, G. G.	Royal Signals	Sec. Lieut.
Kinder, R. N.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)
Kington, C. N.	Royal Air Force	Pilot Officer
Lamond, J. A.	Royal Naval Volunteer Reserve	Sub-Lieut.
Ledger, H. H.	Royal Signals	Lieutenant
Leigh-Clare, H. H. J.	Royal Air Force (V.R.)	Pilot Officer
Locke, C. F.	Royal Naval Volunteer Reserve	Sub-Lieut.
Mackenzie, E. J.	Royal Engineers	Sec. Lieut.
Maddams, L. E.	Royal Naval Volunteer Reserve	Sub-Lieut.
Mallett, L. H.	Royal Army Ordnance Corps	Lieutenant
Marshall, D.	Royal Engineers	Sapper

INSTITUTION NOTES

<i>Name</i>	<i>Corps, etc.</i>	<i>Rank</i>	<i>Name</i>	<i>Corps, etc.</i>	<i>Rank</i>
Maurice, R. B.	Royal Naval Volunteer Reserve	Sub-Lieut.	Ball, C. E.	Royal Naval Volunteer Reserve	Sub-Lieut.
Meredith, E. G.	Royal Naval Reserve	Sub-Lieut.	Barnes, F. E.	Royal Air Force	Pilot Officer
Metcalfe, A. B.	Royal Naval Volunteer Reserve	Sub-Lieut.	Baxter, G. F.	Royal Signals	Sergeant
Miller, G. M.	Royal Engineers	Sec. Lieut.	Bickerdike, S. R.	Royal Signals	Signalman
Nathan, A. J.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)	Bourne, W. J.	Royal Air Force	Pilot Officer
Neave, D. P. B.	Royal Army Ordnance Corps	Lieutenant	Branch, B. G.	Rhodesia Regiment	Sergeant
Osmand, A. G.	Royal Air Force	Sgt. Pilot	Brewer, A. J. S.	Royal Engineers	Sapper
Parkinson, J. B.	Royal Artillery	Sergeant	Brown, H.	Royal Naval Volunteer Reserve	Sub-Lieut.
Partridge, G. H.	Officer Cadet Training Unit	Cadet	Buckland, W. G. N.	Royal Army Ordnance Corps	Lieutenant
Payne, S. L.	Royal Naval Volunteer Reserve	Sub-Lieut.	Burn, J. F.	Royal Engineers	Sapper
Payne, T. C.	Royal Army Ordnance Corps	Lieutenant	Burrow, K. G.	Royal Navy	Wireman
Pearce, P. H.	Royal Engineers	Cadet	Burrows, A. T.	Royal Signals	Sec. Lieut.
Penfold, T. B. D.	Royal Naval Volunteer Reserve	Sub-Lieut.	Burton, D. E.	Royal Signals	Signalman
Percival, F. V.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)	Busby, J. D. A.	Royal Signals	Signalman
Pickard, H.	Royal Signals	Captain	Chetwood, D. H.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)
Pinney, G.	Royal Signals	Lieutenant	Clarke, N. M.	Royal Air Force	A.C.2
Preist, D. H.	Royal Air Force (V.R.)	Flt.-Lieut.	Clough, K.	Officer Cadet Training Unit	Cadet
Prescott, C.	Royal Artillery	Gunner	Cooke, A. B.	Royal Army Ordnance Corps	Staff-Sergeant
Reed, A.	Officer Cadet Training Unit	Cadet	Cooper, S. J.	Royal Engineers	Sapper
Reeves, E.	Royal Army Ordnance Corps	Major	Cranmer, J. M.	Royal Naval Volunteer Reserve	Sub-Lieut.
Reynolds, W. J.	Royal Engineers	Sec. Lieut.	Dale, A. A.	Cheshire Regiment	Lieutenant
Robinson, H. R.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)	Davis, S. C.	Royal Army Medical Corps	Private
Rogers, R. W.	Royal Signals	Corporal	Edelsten, W. K.	Royal Air Force	A.C.2
Sayers, T. C.	Royal Engineers	Sec. Lieut.	Edmonds, E. W. A.	Duke of Cornwall's Light Infantry	Sec. Lieut.
Semken, P.	Royal Naval Volunteer Reserve	Sub-Lieut.	Edwards, E. T. A.	Royal Engineers	Sapper
Shaw, A. L.	Royal Engineers	Sec. Lieut.	Edwards, G.	Royal Army Ordnance Corps	Private
Smith, A.	Royal Engineers	Sapper	Field, H. J.	Royal Air Force	Pilot Officer
Smith, H. R.	Royal Naval Volunteer Reserve	Sub-Lieut.	Fletton, J. C.	Royal Signals	Sec. Lieut.
Smith, K. O.	Welch Regiment	Quartermaster Sergeant	Forsyth, J. G. M.	Royal Signals	Sec. Lieut.
Smith, P. E.	Officer Cadet Training Unit	Cadet	Foster, P. W.	Royal Artillery	Sec. Lieut.
Soutter, C. G.	Royal Engineers	Lance-Corporal	Frodsham, A. F.	Royal Naval Volunteer Reserve	Sub-Lieut.
Spinks, J.	Royal Air Force (V.R.)	Pilot Officer	Greetham, R. F.	Royal Air Force	Aircraftman
Straughen, A. R.	Royal Naval Volunteer Reserve	Sub-Lieut.	Hadland, P.	Officer Cadet Training Unit	Cadet
Strong, R. E.	Royal Engineers	Sec. Lieut.	Hale, N. V.	Royal Signals	Signalman
Tapper, G. W.	Royal Army Ordnance Corps	Lieutenant	Hamilton, F. L.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)
Taylor, R. D.	Royal Engineers	Sec. Lieut.	Hart, E. C.	Royal Air Force	Corporal
Thomas, G. M.	Royal Army Ordnance Corps	Lieutenant	Hay, W. A. H.	The Cameronians	Sec. Lieut.
Thompson, J. J.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)	Haynes, E. R.	Royal Signals	Sec. Lieut.
Unwin, H. J.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)	Hetreed, M. J.	Royal Army Ordnance Corps	Sec. Lieut.
Veale, W. E. C.	Royal Navy	Sub-Lieut. (E)	Holliday, S.	Royal Signals	Signalman
Volum, W. G.	Royal Army Ordnance Corps	Sergeant	Holmes, J.	Royal Army Service Corps	Private
Wade, A. R.	Royal Engineers	Sapper	Hope, J. T.	Royal Army Ordnance Corps	Private
Warne, G. H.	Royal Naval Volunteer Reserve	Sub-Lieut.	Humphreys, H. M.	Royal Artillery	Sec. Lieut.
Waters, G. E.	Royal Naval Volunteer Reserve	Sub-Lieut.	Imison, K. H.	Officer Cadet Training Unit	Cadet
Whitmore, S. F. C.	Cheshire Regiment	Sec. Lieut.	Johnston, J. H.	Royal Signals	Signalman
Young, A. F. B.	Royal Artillery	Sec. Lieut.	Kline, H.	Royal Engineers	Sapper
Students			Laidler, W. R.	Royal Artillery	Lance-Bdr.
Adams, N. F.	Royal Artillery	Gunner	Luing, J. F.	Royal Air Force	Sergeant
Agate, J. S.	Royal Navy	Sub-Lieut. (E)	Marshall, C. J.	Royal Signals	Signalman
Alexandre, A. C.	Royal Signals	Sec. Lieut.	Michaelson, K. B.	Royal Air Force	Leading Aircraftman
Arnold, J. L. S.	Royal Engineers	Corporal	Milne, S. W.	Royal Artillery	Gunner
			Morris, A.	Royal Engineers	Sec. Lieut.
			Munns, J. G. W.	Royal Tank Regiment	Sergeant
			Nicholson, G. G.	Royal Engineers	Sapper
			Pearce, K. W.	Royal Artillery	Gunner
			Peters, R. H.	Royal Naval Volunteer Reserve	Sub-Lieut.
			Plumbly, G. M.	Suffolk Regiment	Sec. Lieut.
			Pridmore, J.	Royal Air Force	Corporal

<i>Name</i>	<i>Corps, etc.</i>	<i>Rank</i>
Rake, C. E. T.	Royal Engineers	Lance-Corporal
Richardson, P.	Royal Engineers	Lance-Corporal
Roberts, A. C.	Royal Signals	Private
Robertson, D.	Royal Engineers	Company Q.M. Sergeant
Robinson, W. E.	Royal Air Force	Leading Aircraftman
Sheldon, P.	Royal Engineers	Sapper
Skipworth, R.	Royal Air Force	A.C.2
Smith, W. D. A.	Royal Air Force	Flt.-Lieut.
South, J. D.	Royal Army Service Corps	Private
Stamps, J. H.	Royal Artillery	Gunner
Starnes, H. W.	Royal Artillery	Gunner
Sullings, F. J.	Royal Signals	Company Q.M. Sergeant
Taylor, J. G.	Royal Army Ordnance Corps	Private
Thompson, R. C.	Royal Signals	Signalman
Townsend, W. C. G.	Royal Artillery	Sergeant
Tucker, E.	Royal Signals	Signalman
Turner, J. C. S.	Royal Air Force	Sergeant
Vigors, P. D.	Royal Naval Volunteer Reserve	Sub-Lieut.
Walker, H.	Royal Army Ordnance Corps	Corporal
Walker, R. G.	Royal Air Force	A.C.2
Watson, K. C.	Royal Signals	Signalman
Weaver, D. G.	Royal Engineers	Lance-Corporal
Wilcox, A.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)
Wilkinson, N. E.	Royal Air Force	A.C.2
Williams, G. L.	Royal Naval Volunteer Reserve	Sub-Lieut.
Williamson, D.	Royal Navy	Sub-Lieut. (E)
Willis, M. D.	Argyll and Sutherland Highlanders	Sec. Lieut.
Woolcombe, W. R. S.	Royal Signals	Signalman
Worman, E. F.	Royal Air Force	Aircraftman

PROMOTIONS AND TRANSFERS OF MEMBERS ON SERVICE WITH H.M. FORCES

(FIRST LIST)

Associate Members

Adye, A. F. C.	Royal Artillery	Major
Beck, W. L.	Royal Signals	Major
Downes, F. A.	Royal Air Force	Flt.-Lieut.
Olson, A. H. F.	Royal Army Ordnance Corps	Lieutenant
Terry, J.	Royal Army Ordnance Corps	Lieutenant
Thurner, W. M. F.	Officer Cadet Training Unit	Cadet
Williams, H. J.	Royal Air Force	Squadron Leader

Graduates

Bousfield, R. H.	Royal Engineers	Lance-Corporal
Buck, J.	Royal Artillery	Lance-Sergeant
Clayton, K. B.	Royal Naval Volunteer Reserve	Lieutenant
Gorman, M. E.	Royal Army Ordnance Corps	Major
Lafin, H. E.	Royal Army Ordnance Corps	Captain
Nicholson, J.	Officer Cadet Training Unit	Cadet
Preston, D. G.	Royal Army Ordnance Corps	Sergeant

<i>Name</i>	<i>Corps, etc.</i>	<i>Rank</i>
Robson, L. F.	Officer Cadet Training Unit	Cadet
Smith, C. C.	Officer Cadet Training Unit	Cadet
Varley, L. J.	Royal Signals	Lance-Corporal

Students

Cartwright, A. E.	Royal Army Ordnance Corps	A/Sergeant
Francis, S. W.	Royal Naval Volunteer Reserve	Sub-Lieut.
Housden, G. A. J.	Royal Artillery	Captain

ELECTIONS AND TRANSFERS

At the Ordinary Meeting of The Institution held on the 22nd February, 1940, the following elections and transfers were effected:—

Elections

Associate Members

Gall, Douglas Crisp.	O'Bow-Hove, Paul Alex- ander, B.Sc.(Eng.).
Gaskell, Maurice Oswin.	Parry, Kenneth.
Gillies, David Comba A.	Stack, Edward Francis R., Captain R.E.
Gray, William.	Tumilty, Hugh Germain.
Hedley, Alan Wilding.	Upadhyaya, Govind Krish- na D.
Herschell, Reginald George.	Walker, Kenneth Douglas, B.Sc.
Hunter, Thomas Norman.	Ward, Percival Alfred.
Matthews, Charles Fred- erick, B.Sc.	
Miller, Henry Arthur.	
Mourant, John Philip B.	

Associates

Bullas, Herbert.	Lussi, Auguste Otto.
Dawson, William James.	Paston-Green, John Henry R.
Gibb, John Purvis.	

Graduates

Baird, Trevor Gordon.	Offer, Ernest John.
Blake, Stanley Alfred J.	Palmer, William Clifford.
Chi, Han-Chen, B.Sc.	Parker, Walter Brian.
Coleman, William David, B.Sc.	Read, William Macartney.
Cooke, George Meredith.	Reid, James.
Fergusson, Robert Brown M.	Scully, Charles Thomas.
Ferrier, James Fisher.	Sowerby, James Mac- Gregor, B.A.
Ghose, Man Kumar.	Stead, Leslie George.
Goodwin, Kenneth Oak- land, B.Sc.	Street, Walter George.
Heanen, John Alexander, B.Sc.	Swinney, Edward.
Hsieh, Shih-Hsin, B.Sc.	Watkins-Ball, Mervyn James.
Kennedy, Edgar James.	Watts, John Raymond.
McBain, John.	Williams, Denis.
McFadden, George Law- rence, B.Sc.	Woodcock, Leslie Gordon.
	Woodford, Reginald Archi- bald.

Students

Ahmad, Riaz, M.Sc.	Ashmawy, Hassan Ahmed.
Appleby, Sidney Jerome.	Ashton, Denys Alban.
Archibald, William John.	Ballantine, Reginald Lloyd.

Students—continued.

Barnett, Alywne Ernest E.
 Beadle, Anthony Crisp.
 Beaumont, James.
 Blackburn, Richard.
 Bottomley, William Dyson.
 Bush, John Henry Cromwell.
 Butler, Charles Edward.
 Chad, Douglas Walter.
 Chambers, Joseph Arthur.
 Chappell, Raymond George.
 Christian, Percy.
 Claydon, Douglas James.
 Colgan, Anthony Joseph.
 Collins, James.
 Cook, Arthur George Ernest.
 Cook, Stephen Lennox.
 Cooke, Roy Arthur N.
 Cooper, Ronald Charles.
 Corbett, James Patrick.
 Cory, Frederick Payne.
 Coulshed, William Francis.
 Elbourn, Roland William.
 Evans, Ivor Stanley L.
 Fairfield, Ian McLeod.
 Fancett, Eric John.
 Forbes, Leonard.
 Fowler, Kenneth Thomas.
 Furby, Dennis Charles.
 Gibson, Howard Phillip.
 Gough, George Stott.
 Groom, Alan Robert.
 Grossett, William.
 Guy, Percy Denis.
 Haines, Edward Robert E.
 Hale, Anthony Peter.
 Hansen, Ivan Charles.
 Harper, Harry Hartridge.
 Harrison, Harold Mellor.
 Henderson, Norman MacLeod.
 Hockaday, Leslie Norman.
 Holdsworth, Maurice Poole.
 Imber, Richard Charles.
 Isted, Charles Robert.
 Jackson, Peter Ernest.
 Jennings, Henry Walton.
 Joshua, Josh S., B.Sc.
 Keith, Ian Duncan.
 Kingston, Ernest Harold.
 Kirkwood, George.
 Leicester, Graham Alfred.
 Lewitt, Victor Max.
 Lott, John Edward.
 Lunau, Frank William.
 McBean, Hamish Russell.
 Machent, Harry.
 Mase, Brian James.
 Mattos, Albert Venancio.
 Melton, Charles Newcombe.
 Mercer, Arthur Keith.
 Metz, Philip Henry.
 Mills, John Ernest P.
 Mitchell, Alexander Henry.
 Morrison, Norman.
 Natarajan, V.
 O'Donnell, Alexander.
 Page, Stephen.
 Palmer, Clifford Oliver J. G.
 Palmer, Francis Charles W.
 Panchamritam, N. R.
 Panter, Francis Hugh.
 Phillips, Brian Selsey.
 Price, Gordon Wesley.
 Prout, Reginald Wilfred.
 Puttock, Ronald William.
 Qualtrough, John Davidson.
 Ramabhadran, G. N., B.A.
 Rawling, Robert Sydney.
 Richardson, William.
 Roberts, David Edmund C.
 Roberts, John.
 Robertson, Robert George.
 Rose, John Cyril.
 Sanderson, John Laurence.
 Saunders, Joseph Brown.
 Saxby, Francis Hugh.
 Scattergood, Gordon Edwin.
 Seckham, Charles Cooper.
 Selby-Lowndes, Edward Douglas W.
 Shapland, Albert John.
 Shenton, John.
 Simmons, James Richard.
 Smail, James Elliot.
 Smith, Albert Fenton.
 Smith, Thomas Patrick.
 Stephen, Keith.
 Taylor, Ralph Clifton.
 Teale, Alan.
 Thackwell, Eian Alfred.
 Venkatesan, Sivaram.
 Vick, Alfred Spencer.
 Vickers, Cyril.
 Viegas, Fernando, B.Sc.
 Walker, Eric Frederick.
 Wardle, Leonard George.
 Westcott, John Hugh.
 Wighton, John Robert.
 Willson, Leslie Robert.
 Wolfendale, Frank.
 Younger, Joseph Henry.

*Transfers**Associate Member to Member*

Boyce, John Samuel.	Donkin, Bryan, B.A.
Dawson, William John M.	Pittaway, Kenneth.
Dennis, William Edwin, Lt.-Col.	Singh, Saudagar, M.Sc.
	Varley, Robert.

Associate to Associate Member

Bray, Percy Archibald.	Hayden, William Benjamin.
Dallow, Norman Richard.	
Dennes, Howard Gay.	Thomas, Alfred Morris, B.Sc.
Ellis, Leonard George.	

Graduate to Associate Member

Aston, Leonard George.	Lewis, Hexell Arthur, B.Sc. (Eng.).
Ball, Brian Francis, B.A.	Lewis, William Kenneth.
Brook, George Henry.	Mackie, Andrew Douglas.
Clark, William Brindley.	Pearce, Charles Arthur R., M.Sc.(Eng.).
Cooper, Arthur Ronald.	Pearce, Kenneth Maxwell.
Dew, Clement Edgar.	Ray, Binoy Bhushan, M.Sc. (Eng.).
Dharap, Prabhakar Waman.	Rice, Richard Henry G.
Donald, William Horace.	Roynon, Frank Goodner.
Hackett, Miss Winifred, B.Sc., Ph.D.	Sims, Kenneth Edward, B.Sc.(Eng.).
Hamilton, Robert, B.Sc. (Tech.).	Sutton, Percy William, B.A.
Harrison, Douglas, B.Eng.	Thompson, Henry Christian, B.Sc.
Jarvis, Harold Frederick.	Wight-Boycott, Alexander Hubert P.
Jewitt, Eric, B.Sc.(Eng.).	
Kirkpatrick, Kenneth Sutton.	
Laycock, Leonard Spencer.	

Student to Associate Member

Webster, James Gordon, B.E.

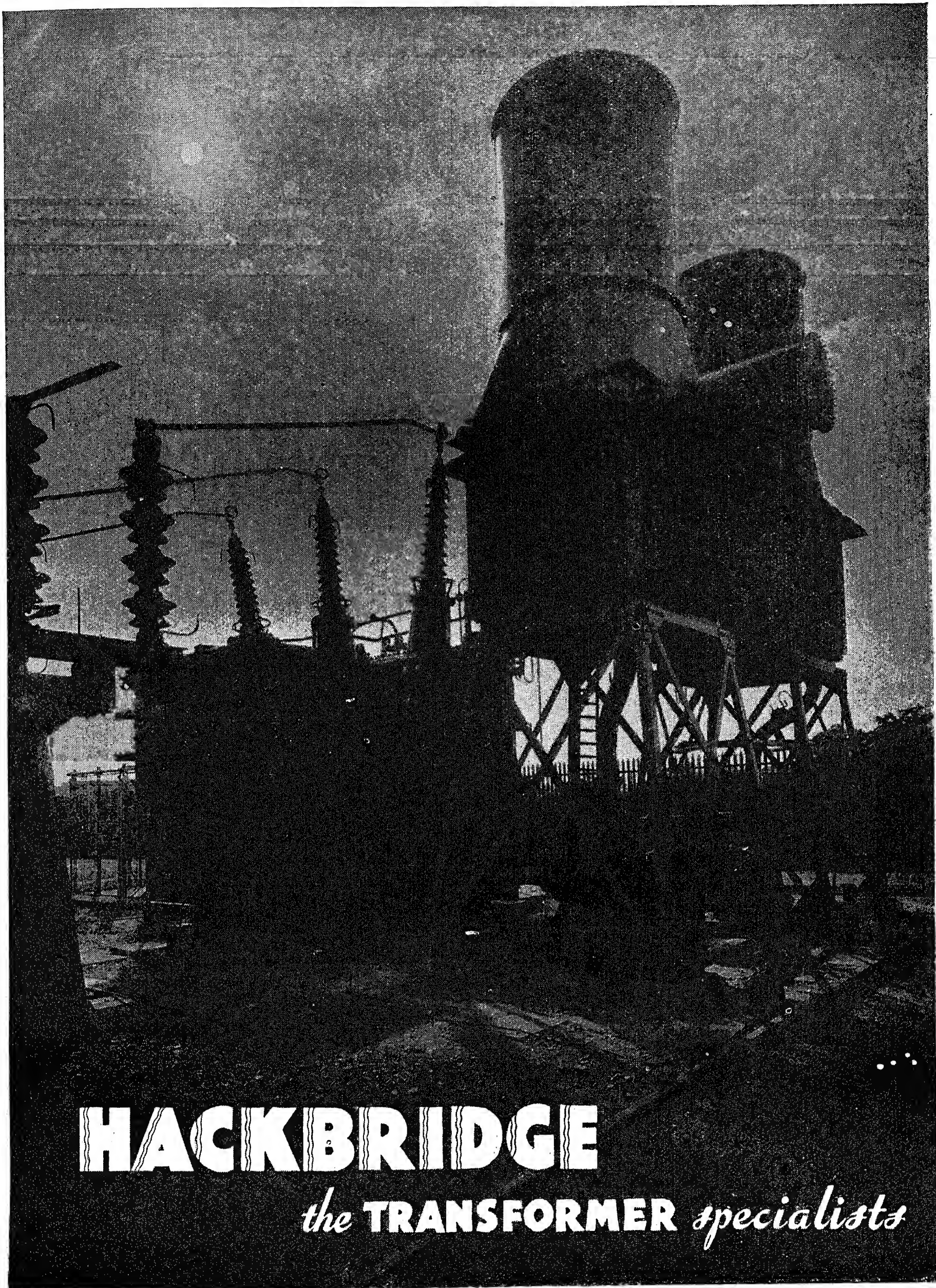
Student to Associate

Chapman, George Henry.

The following transfers were also effected by the Council at their meeting held on the 8th February, 1940:—

Student to Graduate

Allan, James.	Martin, Kenneth Spencer.
Antram, Alfred Harry.	Meiklejohn, William Kenneth.
Burnand, Donald William, B.Sc.(Eng.).	Newman, Henry Daniel, Flight-Lieut.
Chapter, Colin Falconer.	Parkin, Peter Hubert, B.Sc.(Eng.).
Coombs, Frederick Leslie.	Patel, Chinubhai Manibhai.
Cox, Ronald Edgley, B.Sc.	Pikett, Cecil Charles.
Crumblehulme, Leslie Ashton.	Rogers, Robert William.
Donovan, Timothy Denis.	Savage, John Openshaw.
Ferguson, Oswald.	Spinney, Roger Edwin, B.Sc.
Harris, Frederick Llewellyn.	Sutton, George Gurney, B.Sc.(Eng.).
Hart, Francis.	Walker, Sydney Alfred.
Harvey, John Alistair F.	Wallis, James Grainger.
Hay, William Jean, B.Sc.	Watson, Archibald Dick C.
Hewson, John Elam.	Wilkinson, Donald Frederick, B.Sc.(Eng.).
Kington, Cecil Newton, B.Sc.	Wyke, Richard Edgar B.
Long, George Richard.	
Lysons, Horace, B.Sc.Tech.	

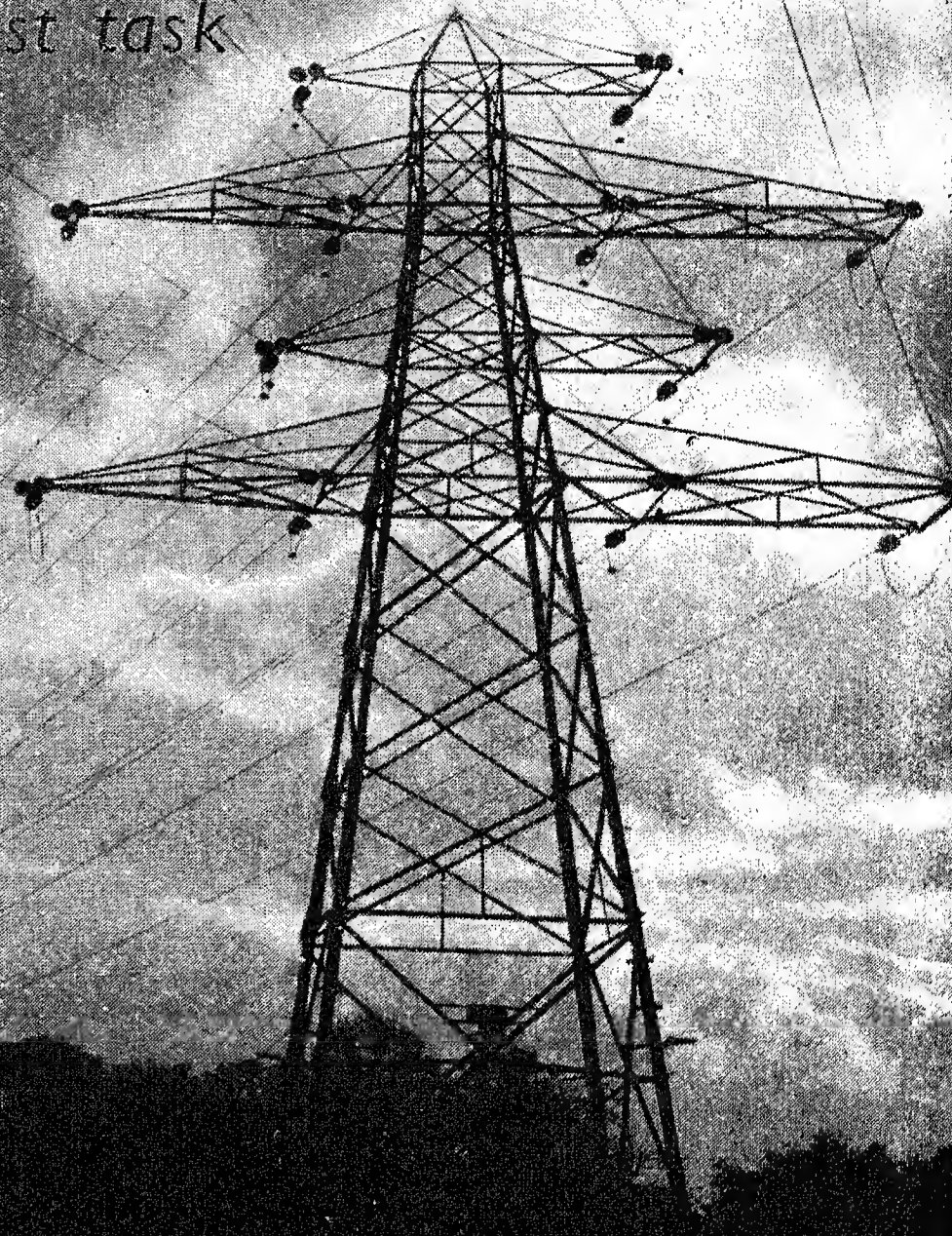


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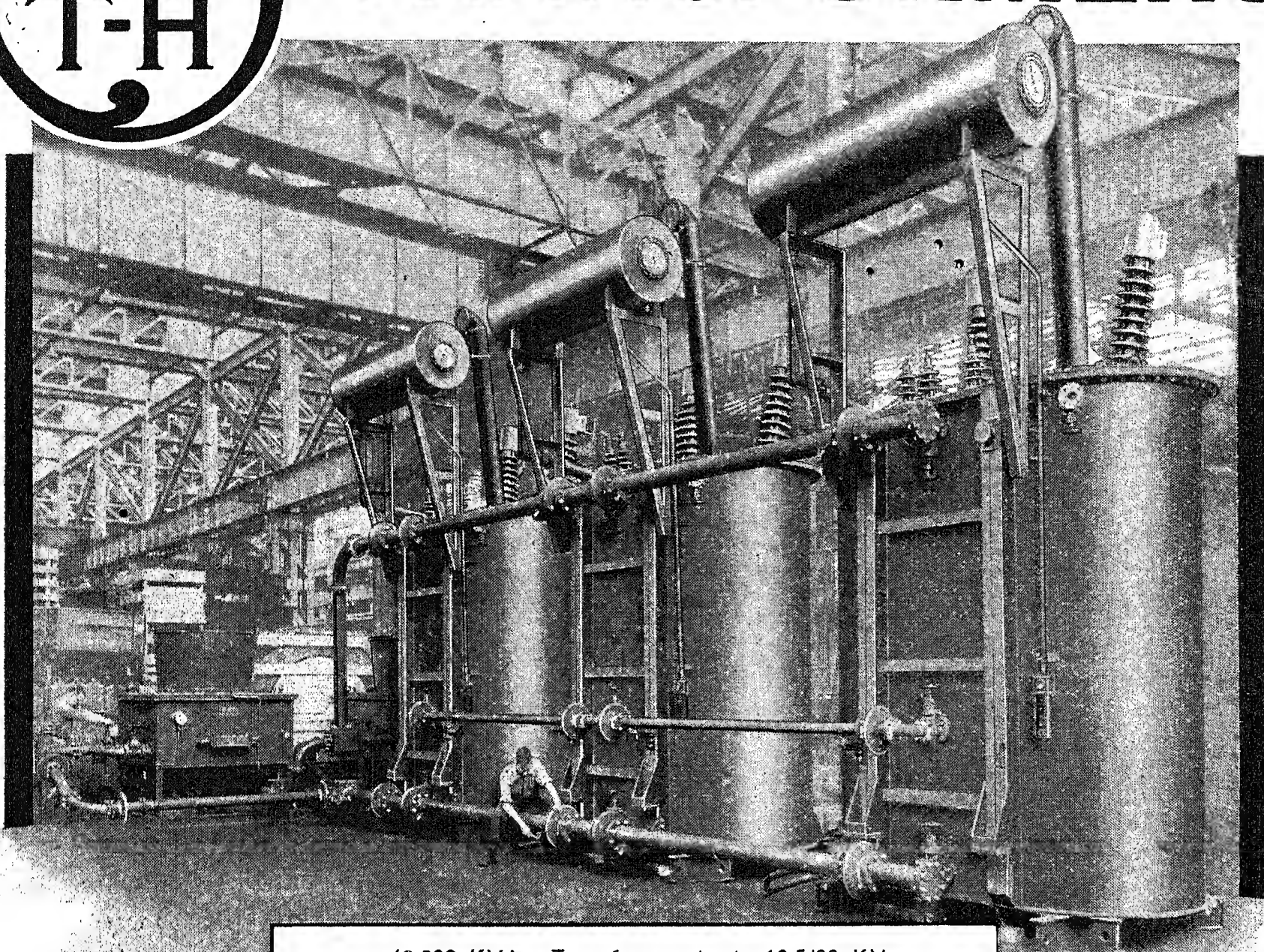
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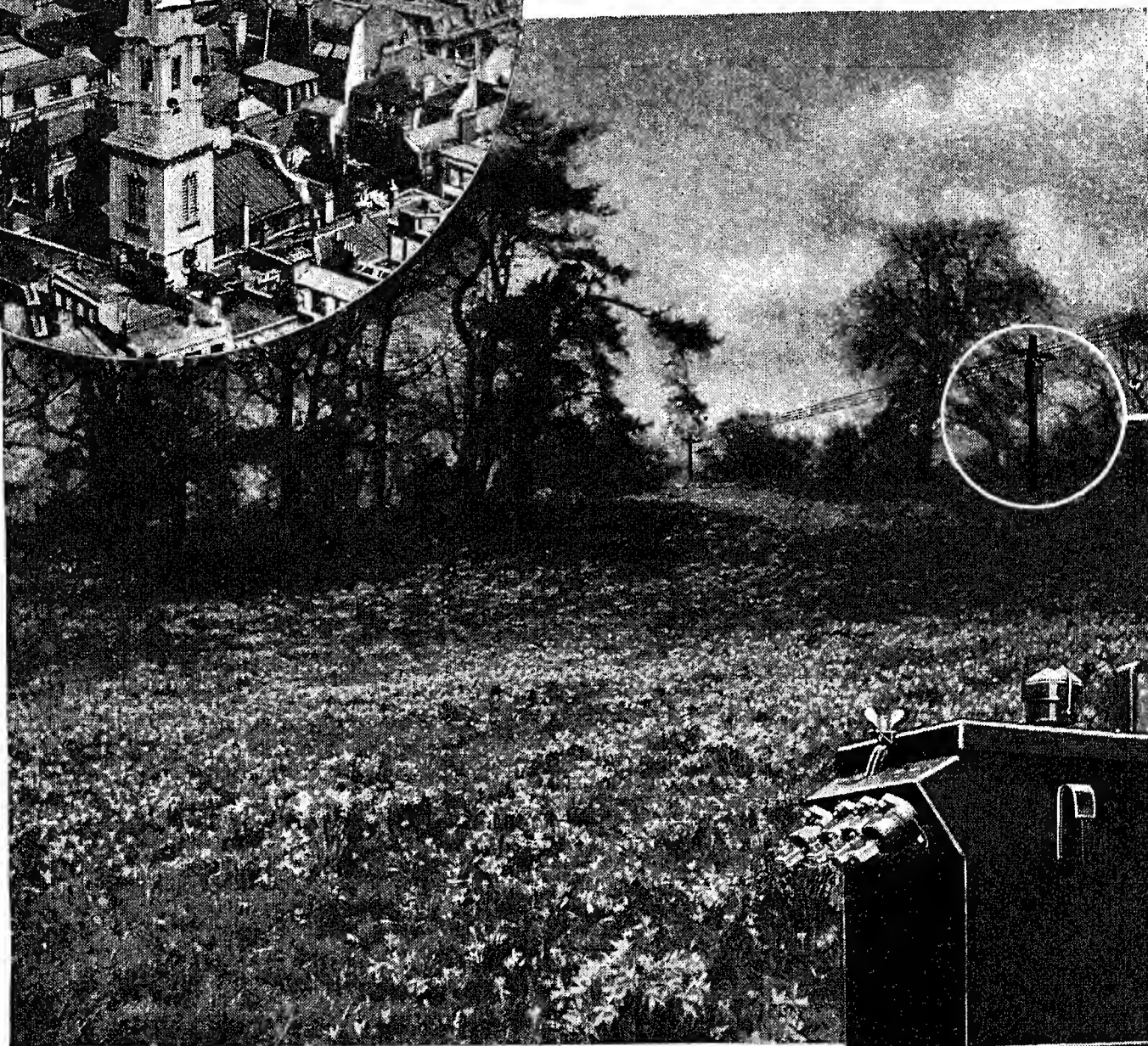
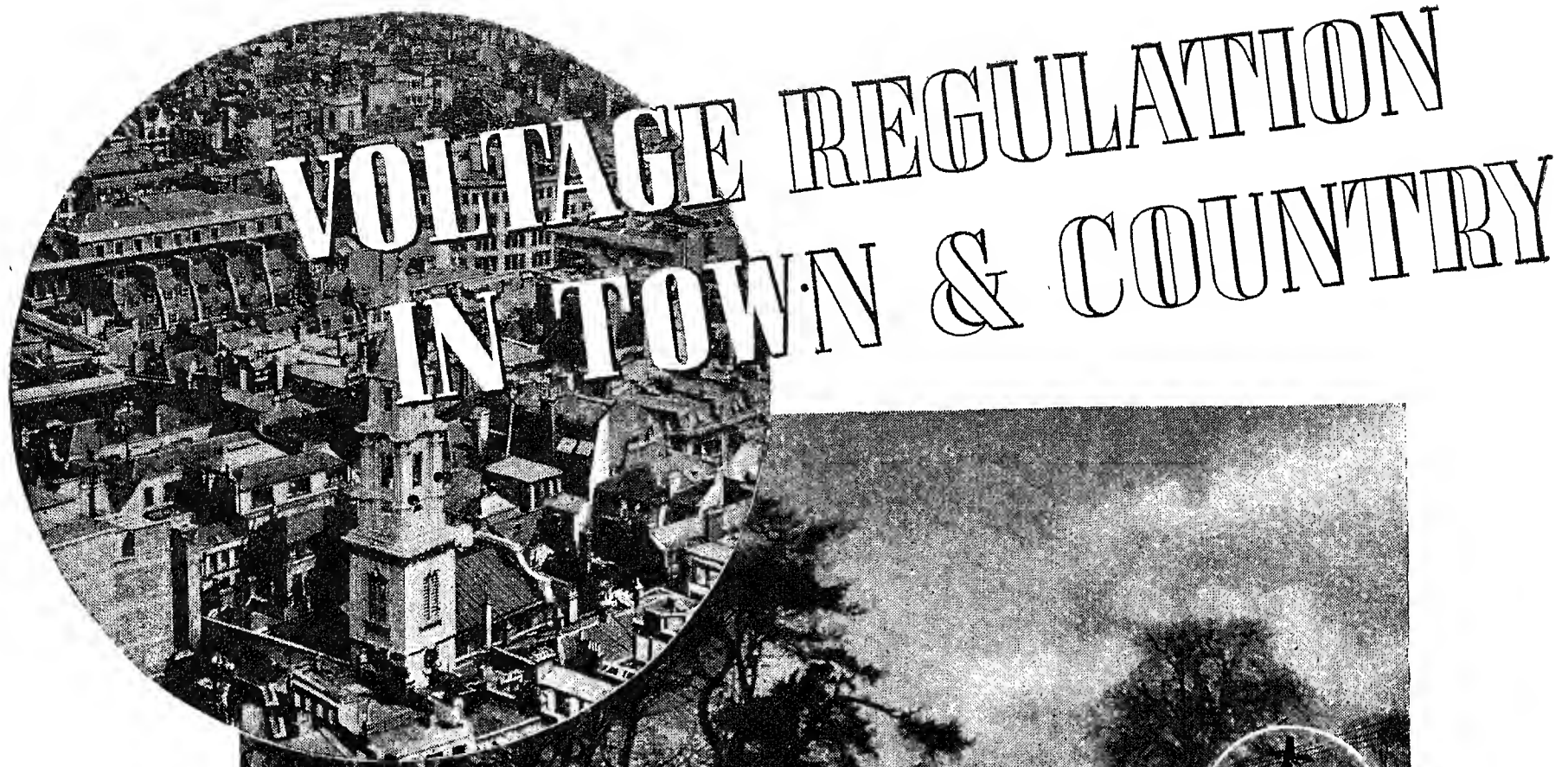
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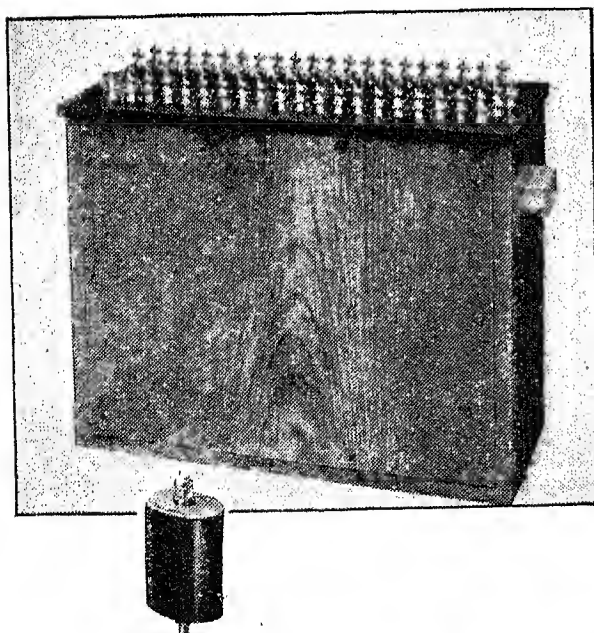
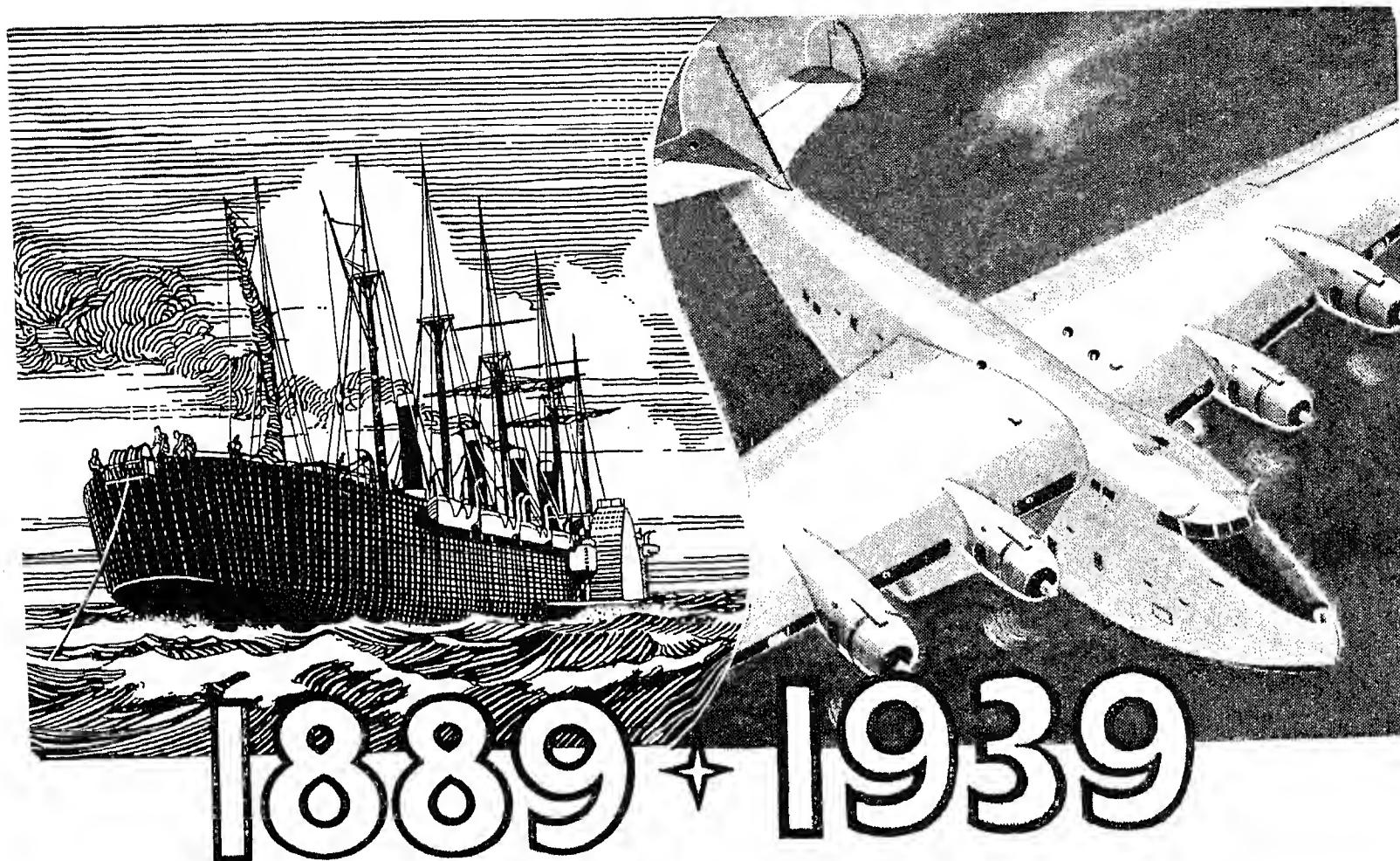
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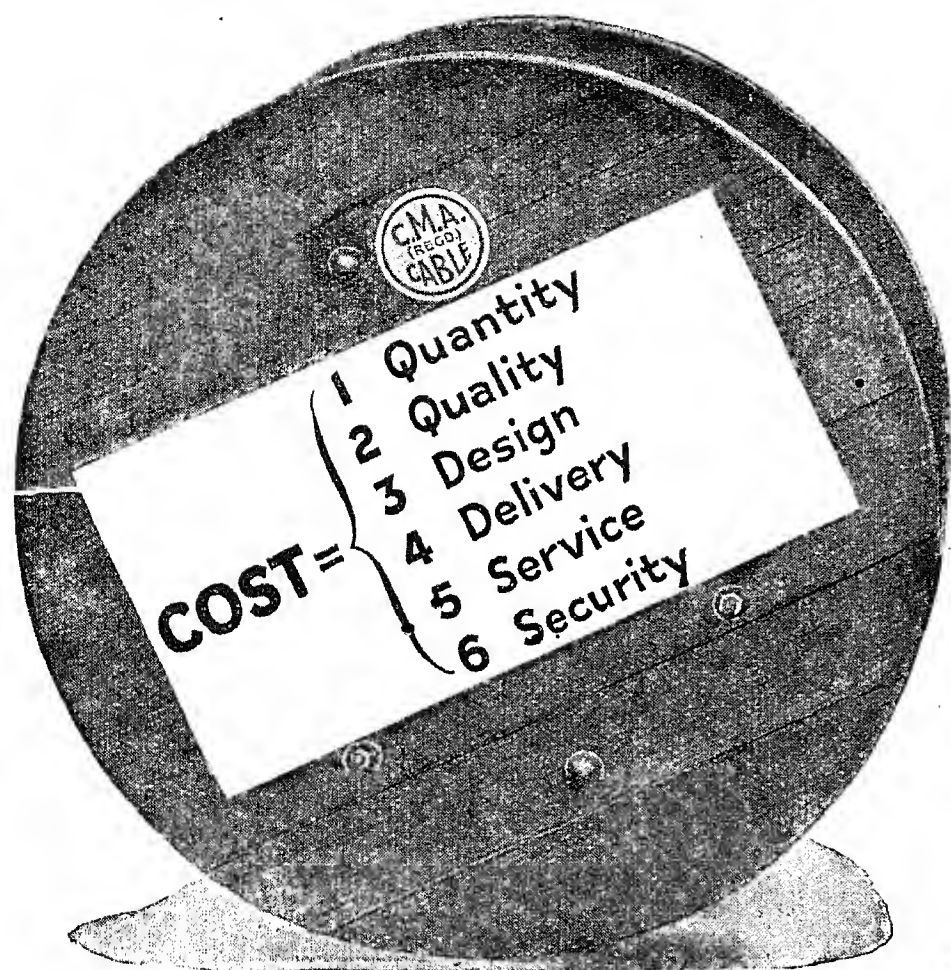


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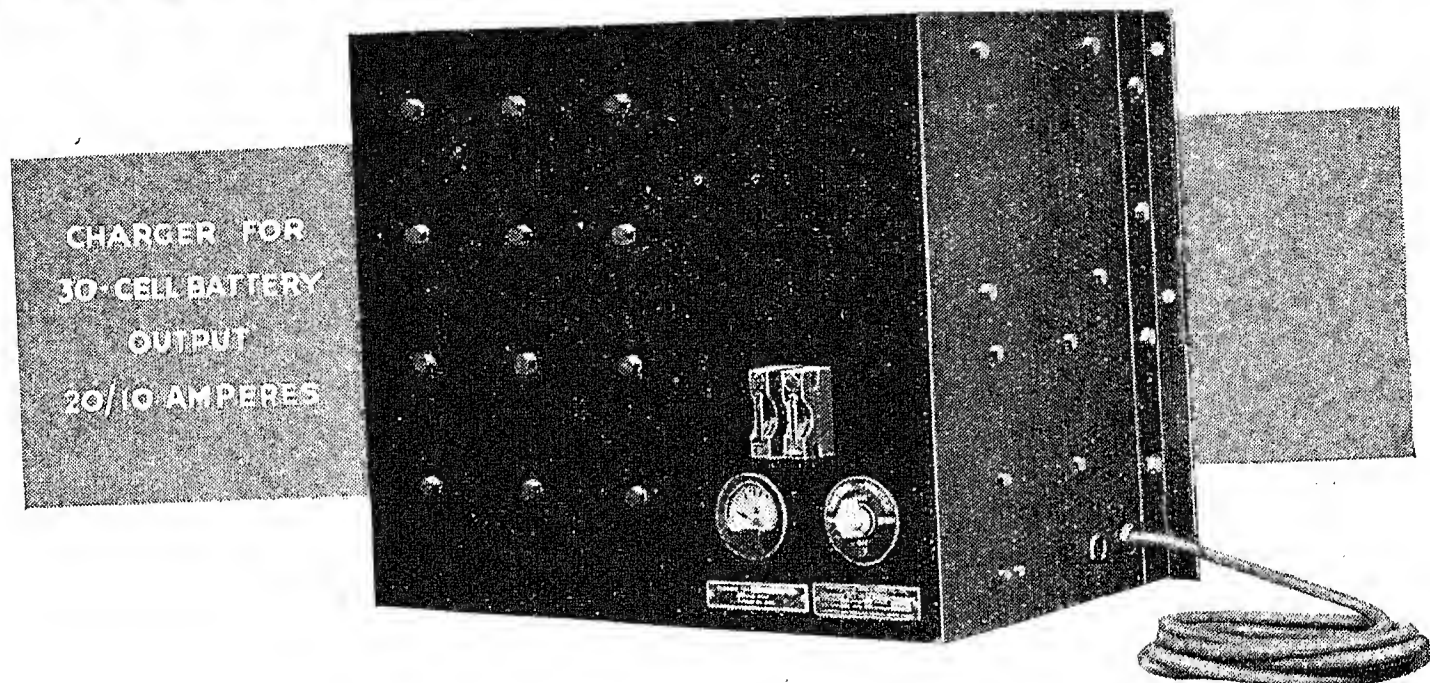
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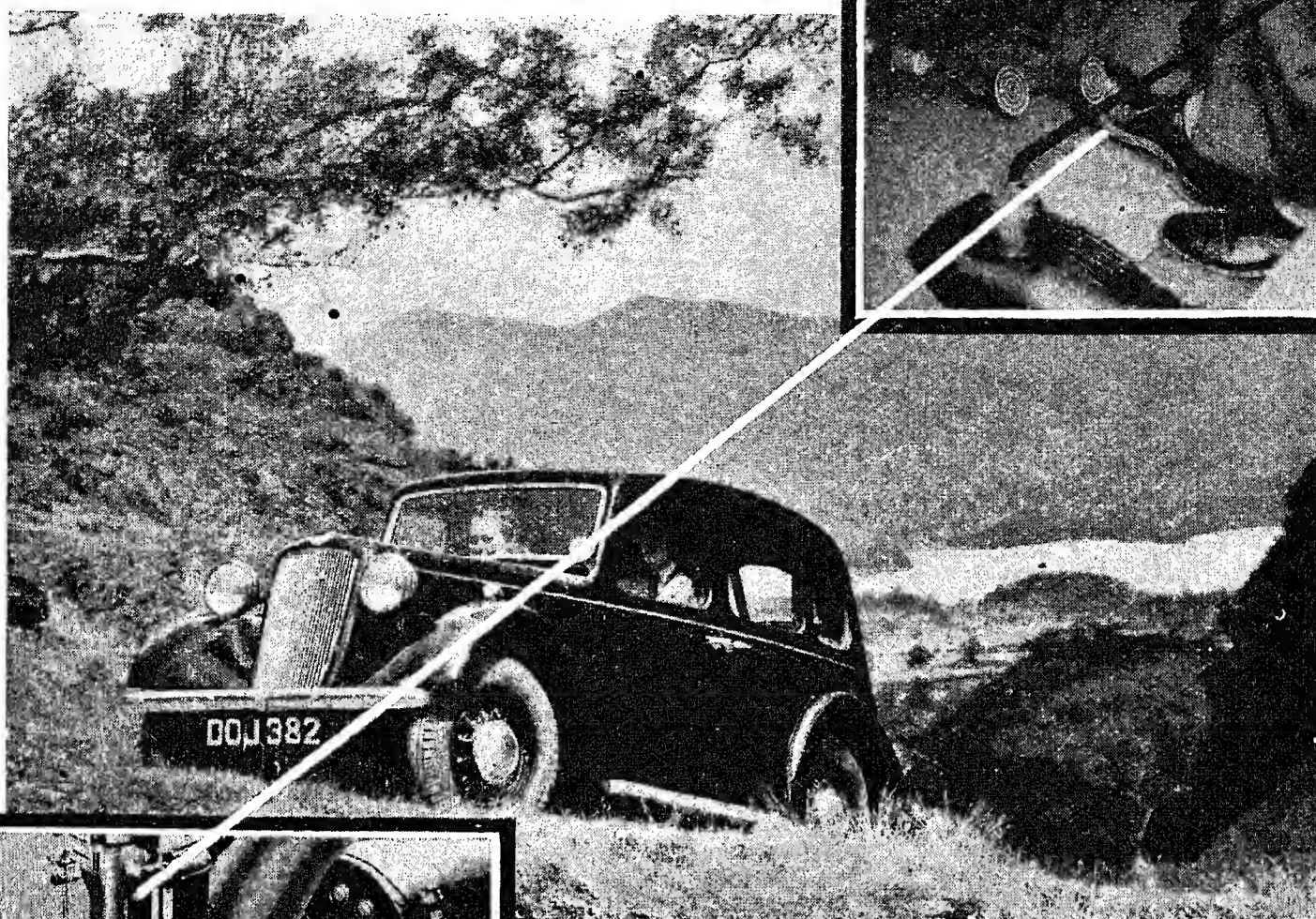
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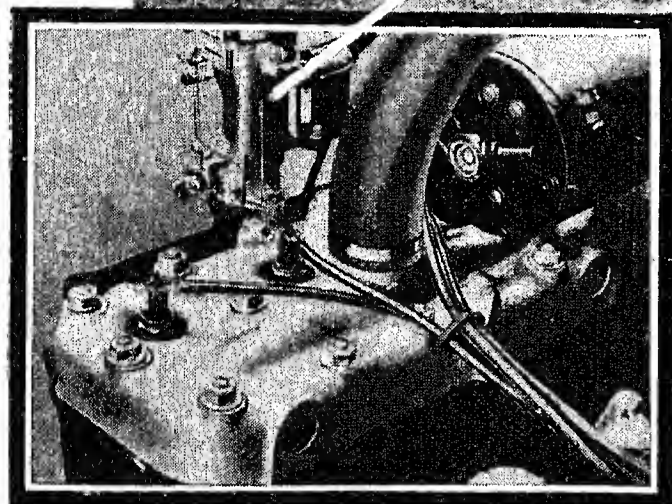
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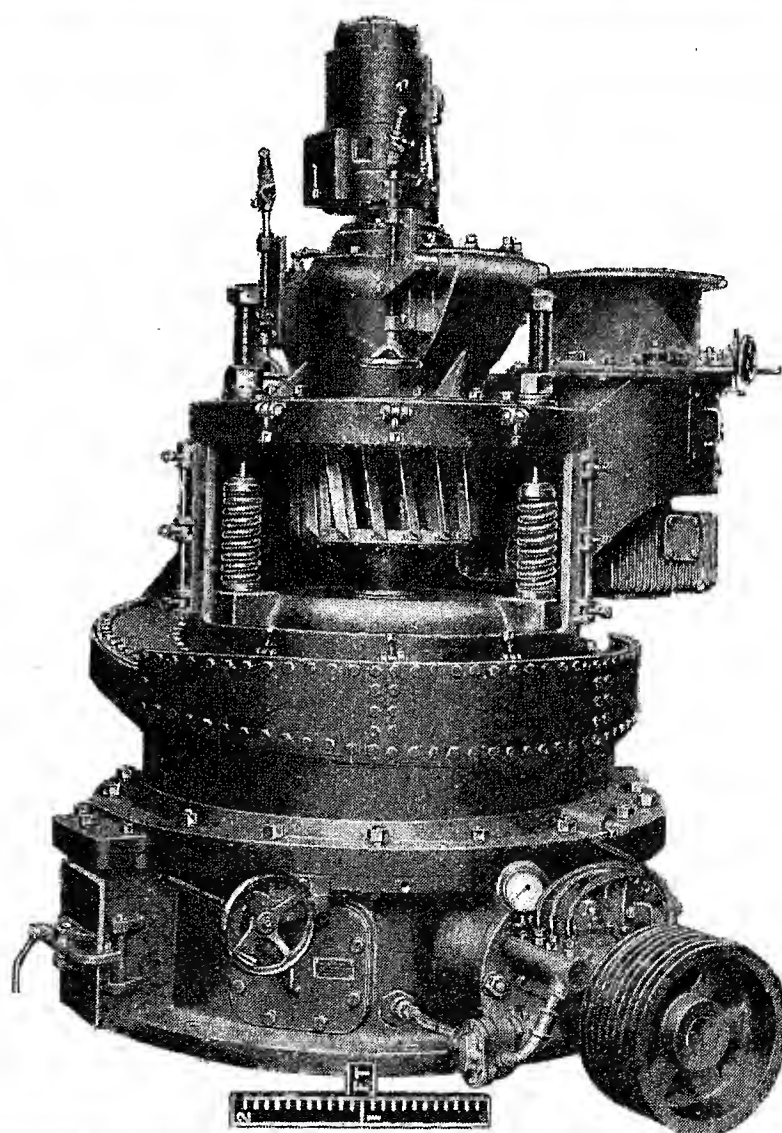


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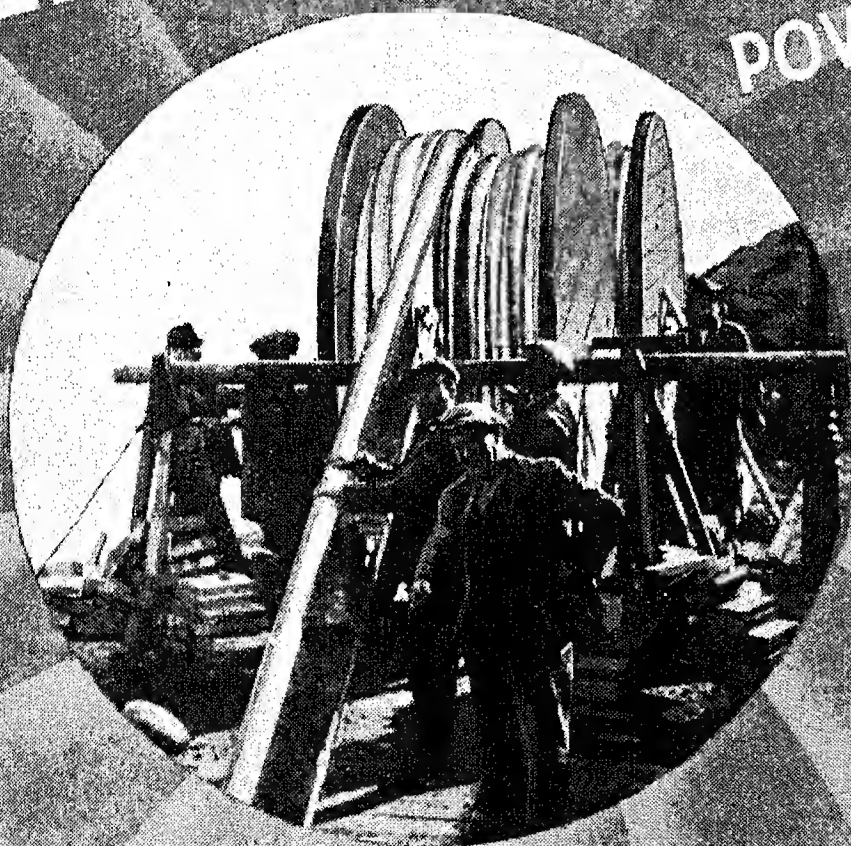
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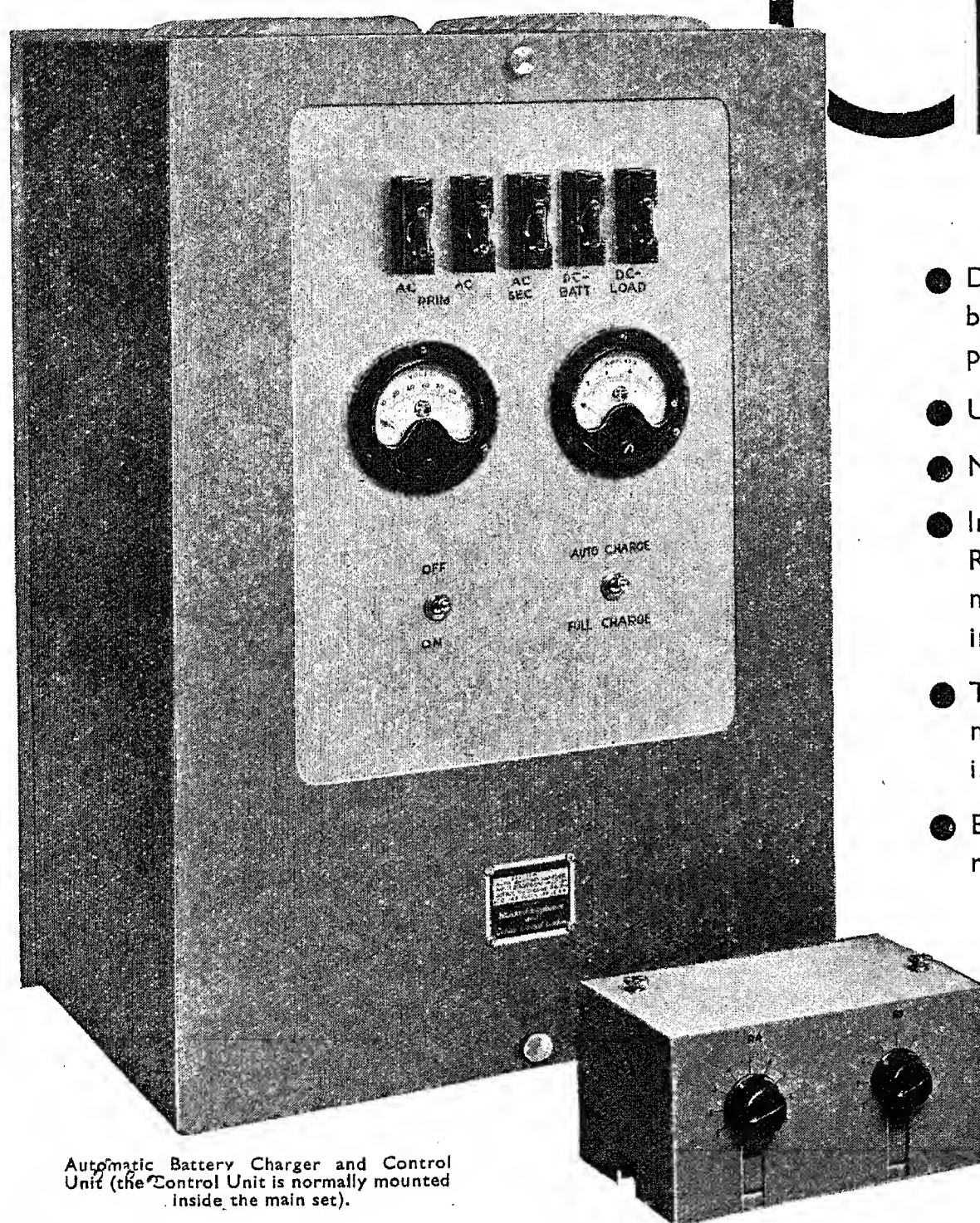
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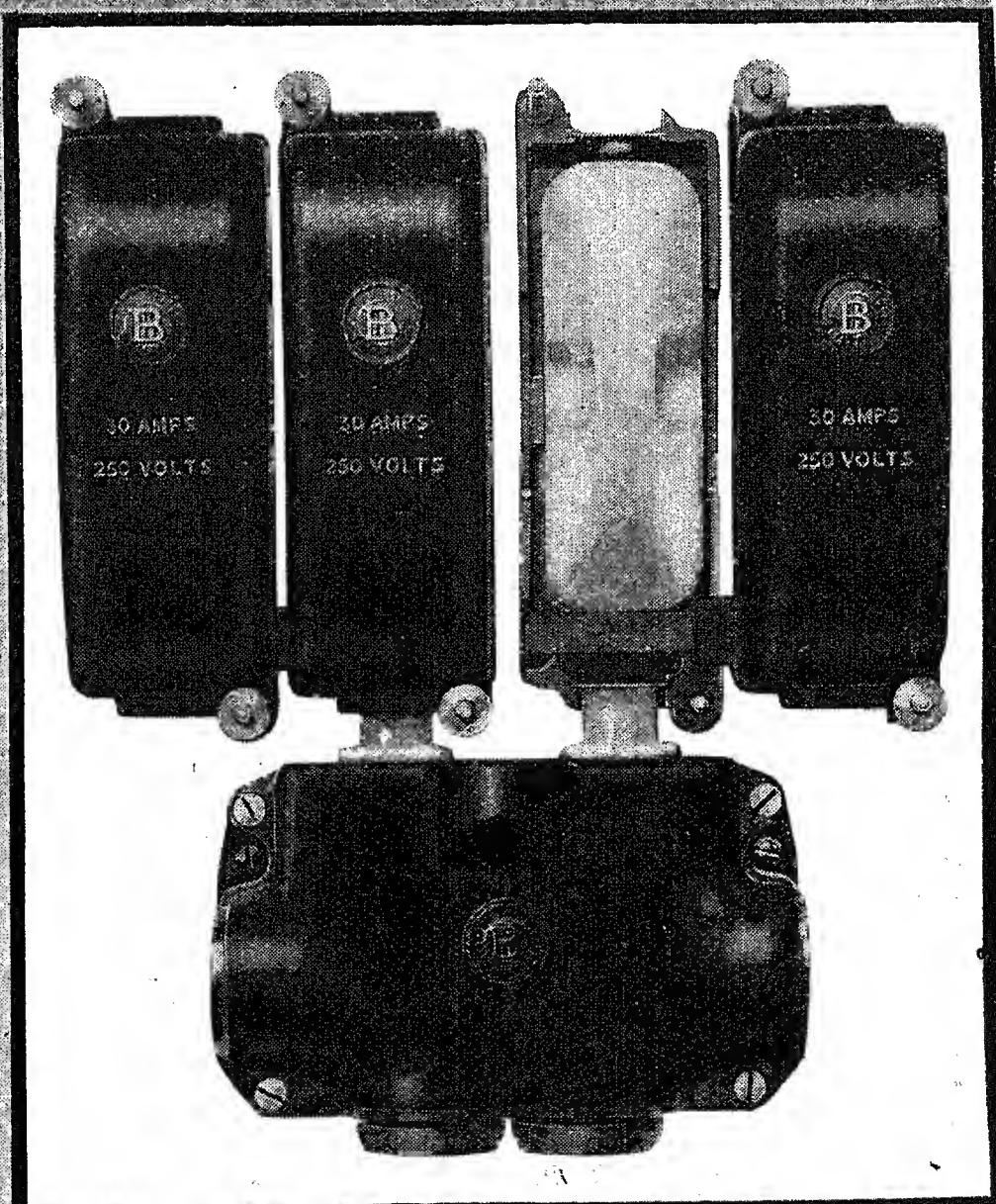
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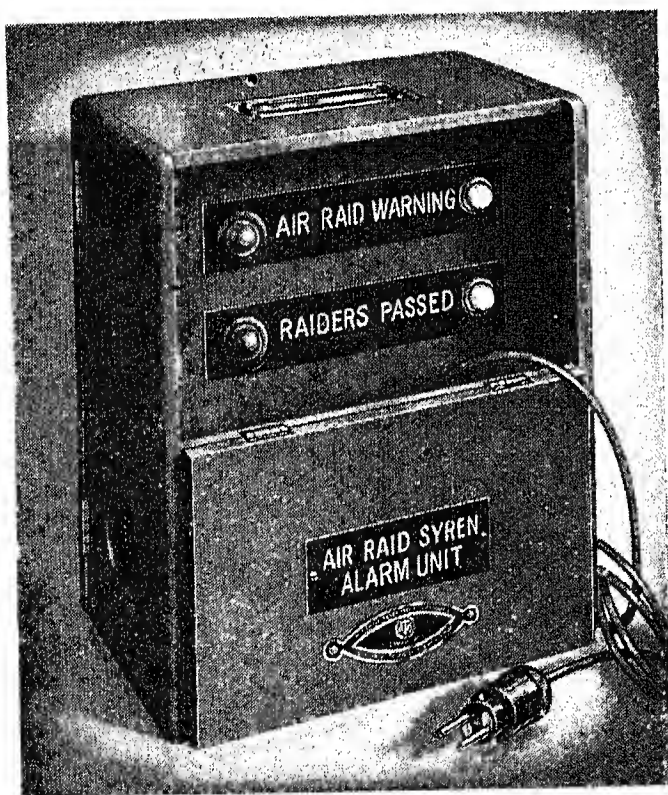
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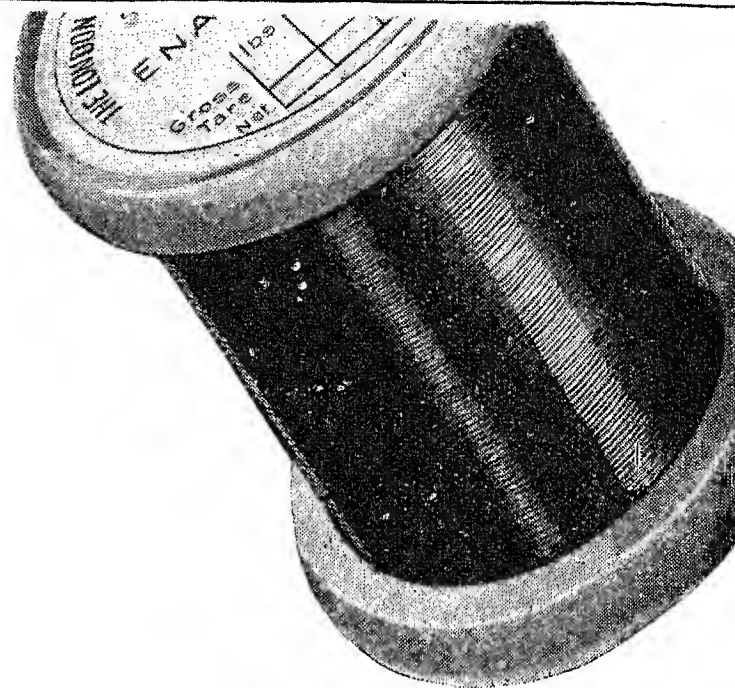
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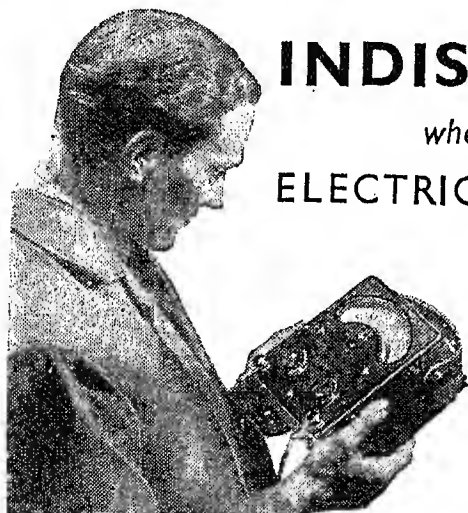
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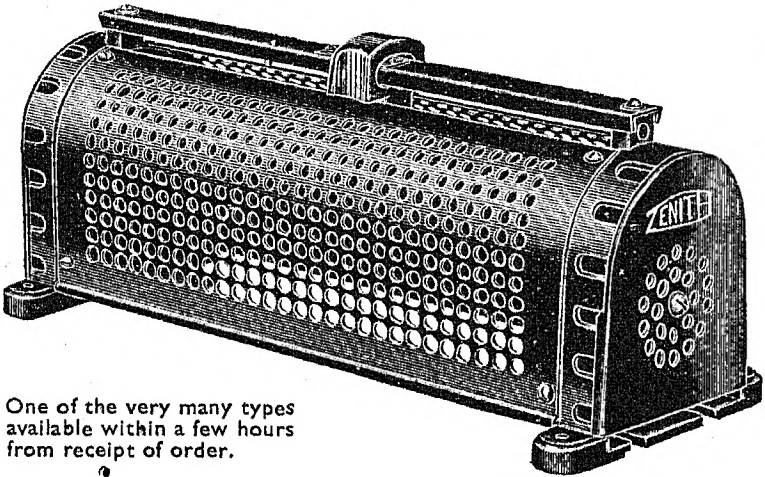
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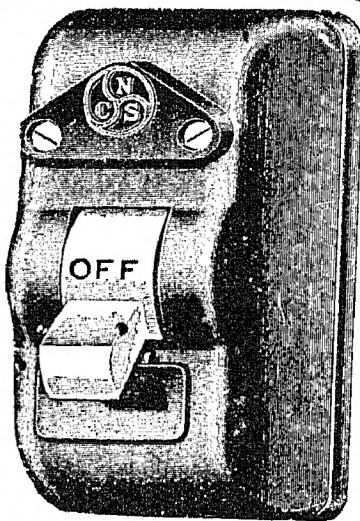


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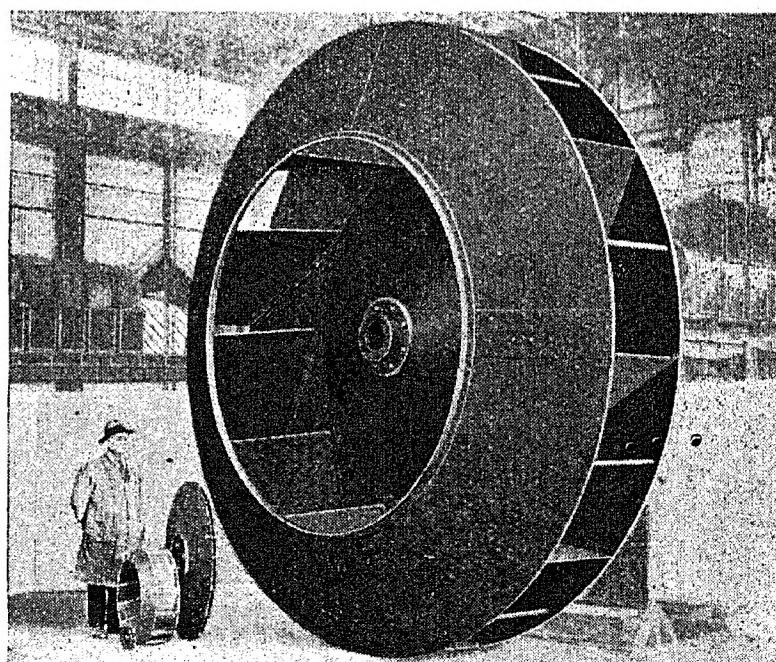
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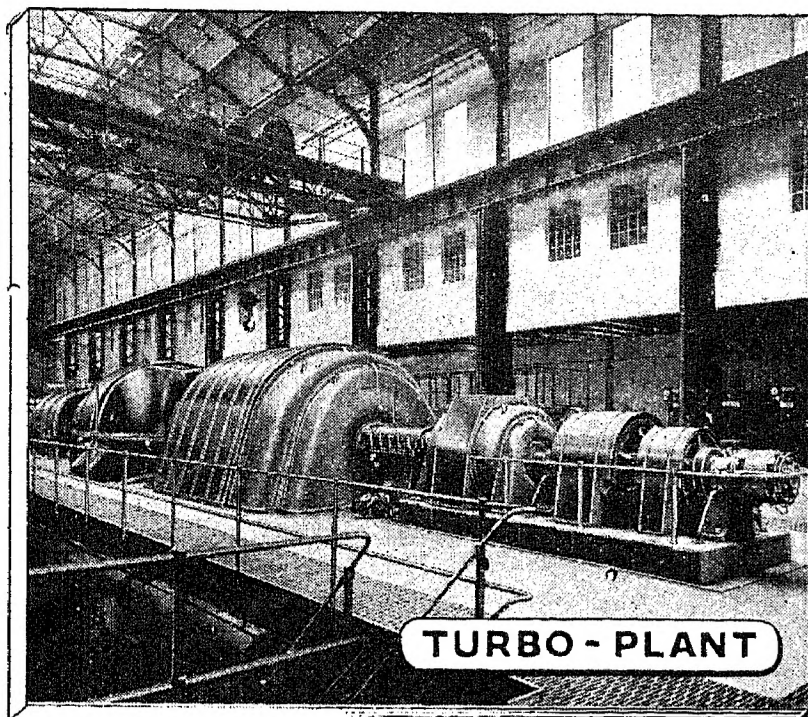
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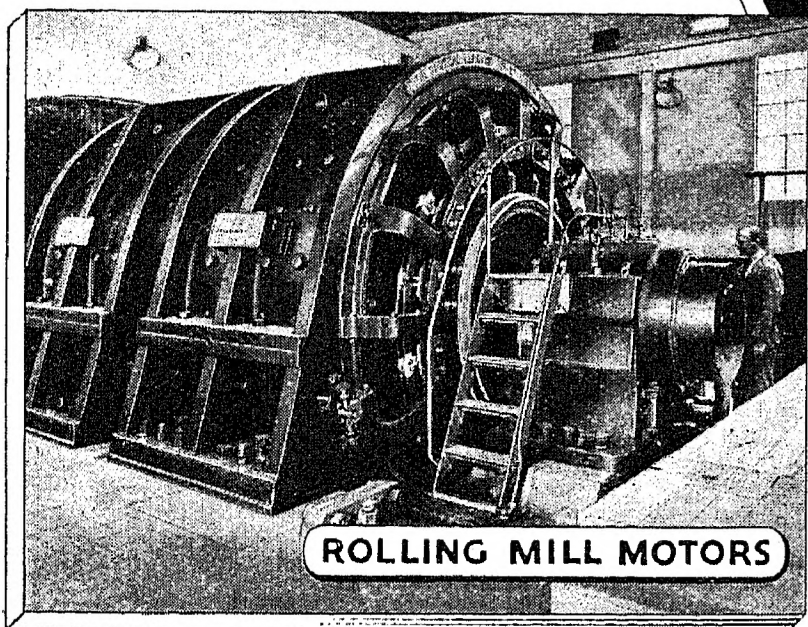
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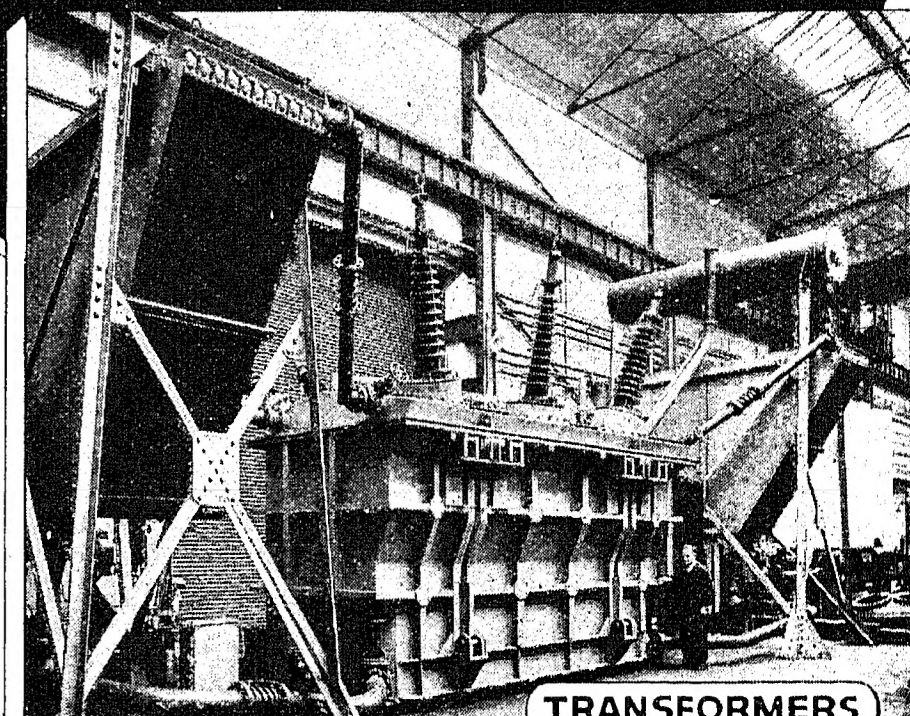
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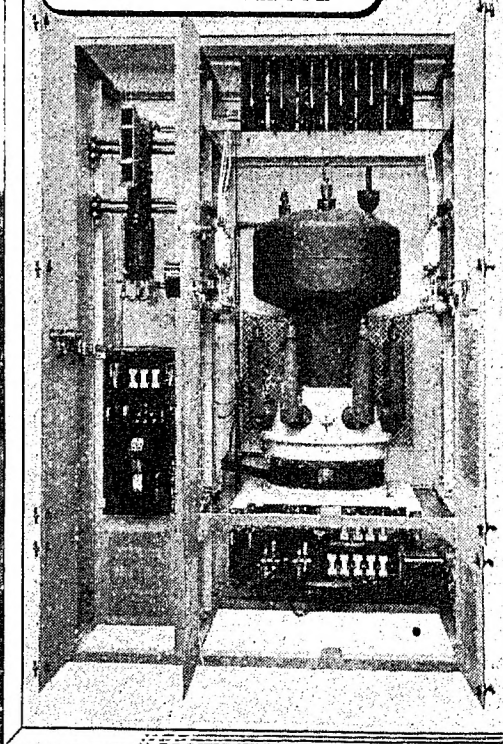
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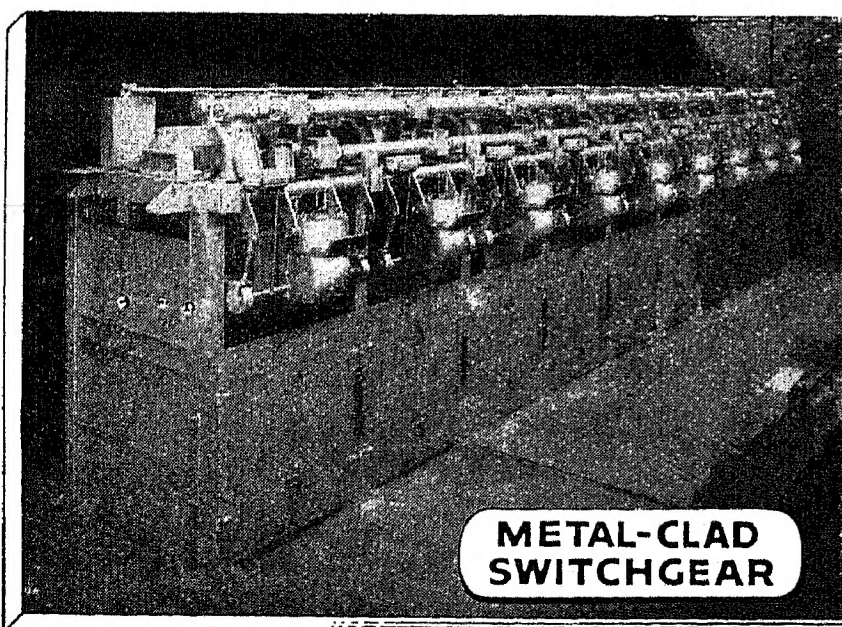
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